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Title: Critical Conditions for Carriage Passage at the Support Jack for Uphill Yarding

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Critical skyline and mainline tensions were identified as the conditions necessary for successful carriage passage uphill over an intermediate support jack. These critical tensions were measured during field tests and compared with predicted values from weightless line, rigid link, and catenary analyses. All three analyses predicted critical skyline tensions within the range of field measured values while critical mainline tensions were consistently overestimated.

An existing computer multispan skyline analysis program (MSAP) was modified using the rigid link analysis to check for critical tensions at the support jack. A comparison of MSAP results with measured field values showed good agreement for skyline tension and conservative estimates for mainline tension. As an alternative to the computer program, a graphical method for determining the critical midspan deflection was developed, patterned after the chain and board method.

The analysis and test results indicated that present multispan

design criteria for uphill yarding were overly conservative in many instances. To evaluate the economic effects of designing below system potential, yarding costs/mbf were compared, on a typical setting, based on predicted payloads using present and new design methods. Results of this comparison, based on payload effects only, showed that a considerable economic advantage existed when the new design procedure was used.

Critical Conditions for Carriage Passage at the Support Jack for Uphill Yarding

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CRITICAL CONDITIONS FOR CARRIAGE PASSAGE AT THE SUPPORT JACK FOR UPHILL YARDING

I. INTRODUCTION

Much of the remaining commercial timber in the Pacific Northwest is on steep, constant slopes where road construction is inherently difficult and expensive. Stricter environmental constraints have added to already high costs of road construction and in many instances have prohibited road locations on steep terrain entirely. Conventional cable systems require road densities that may not be economically feasible and create ground disturbances that may not be environmentally acceptable on steep terrain. While aerial systems may be environmentally acceptable, high operating costs exclude their use in many low volume areas. On the other hand, multispan systems can yard beyond the limits of conventional systems with lower road densities. The savings in road building costs can offset the higher yarding costs of skidding over greater distances. In addition, low levels of ground disturbance enable multispan systems to compete favorably with aerial systems from an environmental standpoint. For these reasons, multispan systems have been able in specific instances to more effectively harvest timber from steep terrain than either conventional cable or aerial systems.

The original multispan system introduced into the United States from Europe was designed primarily for downhill yarding. With this system, a turn of logs secured to a skyline carriage was lowered downhill over the intermediate support jack under the influence of gravity, with the mainline acting as a snubbing line. A flat chord slope between the head spar and intermediate support could result in failure of the carriage to pass the support jack (Binkley and Sessions, 1978).

Recently, the multispan system has been utilized in both downhill and uphill yarding configurations. Where a ridgetop road system already exists, uphill multispan logging is an especially attractive alternative. In addition, because the turn of logs are being pulled to the landing by the mainline, it is no longer necessary to fully suspend the log free of the ground. Lower support spars are possible resulting in reduced rigging costs because of this relaxed constraint.

Since uphill yarding with a multispan system is a relatively new technique (at least in the United States) not all of its operating characteristics are well known. Critical conditions for successful carriage passage uphill over the intermediate support jack have not been established. Design has relied on rules of thumb developed from a limited amount of field observations.

In order to use the multispan uphill system to its fullest potential, a knowledge of the critical conditions for successful carriage passage over the intermediate support jack is necessary. The analysis and field testing undertaken in this study represents an attempt to identify and predict these critical conditions.

II. LITERATURE REVIEW

The literature indicated no previous attempts to analyze or test the critical conditions for carriage passage over an intermediate support during uphill yarding. Carson (1975) presented a computer program for a multispan skyline system which determined: (a) the load that can be supported at any point, (b) the tension and deflection resulting from a given skyline line length and load, and (c) the load at any intermediate support assuming that the skyline slides freely through a frictionless, fixed support jack. Although the loads near the support jack were predicted, no critical boundary conditions for uphill carriage passage were defined. Amstutz (1942) described a graphical solution to determine the length of skyline existing in adjacent spans between intermediate supports for a continuous line cableway. He considered the effects of friction at the fixed support jack on the sliding cable but made no reference to successful carriage passage. Binkley (1965) discussed the possibility of a skyline lifting out of a support jack as the payload moved from span to span. He recommended the use of Carson's multispan program to identify when lift out would occur. Hensel (1977) made reference to the necessity of a "taut" skyline in his analysis of the Wyssen Multispan System.

McGonagill (1977) stated that for uphill yarding using intermediate supports "the break in the span chord must be kept under 35% for satisfactory operation." Binkley and Sessions (1978) stated similar conclusions more conservatively. "Field observations indicate that loaded carriage passage uphill over supports is quite smooth for loaded midspan deflections of six percent or less and grade breaks of 35% or less. ... larger midspan deflections may be tolerable, particularly at steeper chord slopes."

The recommendation of six percent maximum midspan deflection and chord slope break not exceeding 35% appears to be the only written guidelines for designing multispan skyline systems. This recommendation was based on a limited number of field observations and measurements.

III. ANALYSIS DEVELOPMENT

The multispan skyline system uses intermediate supports to increase the load-carrying capacity of the system. With the addition of intermediate supports, a new constraint is added to the objective of moving a carriage and payload along the cableway from the tail spar to the head spar. Some force has to be applied to the carriage to move it along the cableway and over the intermediate support without exceeding the critical conditions which prevent carriage passage over the support jack. For the uphill yarding case, the mainline tension provides this force. As the carriage moves along the skyline under the influence of the mainline, the skyline is deflected some by the effect of the gross payload (weight of carriage plus payload) and the mainline tension. Failure of the carriage to pass over the support jack can be caused by: (1) insufficient mainline tension to move the carriage past static equilibrium conditions; or (2) critical geometry conditions developing at the support jack. Detailed discussion of these conditions follow.

Inclined Plane Analogy

Consider the inclined plane illustrated in Figure 1 which supports a round wheel. Neglecting friction, the forces acting upon the wheel are represented by W, the weight of the wheel; R, the normal force provided by the plane surface; and T_m, the tension in the mainline attached to the center of the wheel. If the sum of the forces on the wheel equal zero, and the wheel is not moving, the wheel will remain stationary on the plane. In this condition of static equilibrium, the resultant force of T_m and W must be exactly equal and opposite to the normal force, R. Since the normal force acts perpendicular to the plane, then the resultant of the weight and mainline must also bisect the plane surface into two equal angles of 90^o. The mainline has a limiting tension to maintain static equilibrium. For the wheel to advance up the plane, this limiting mainline tension must be exceeded.

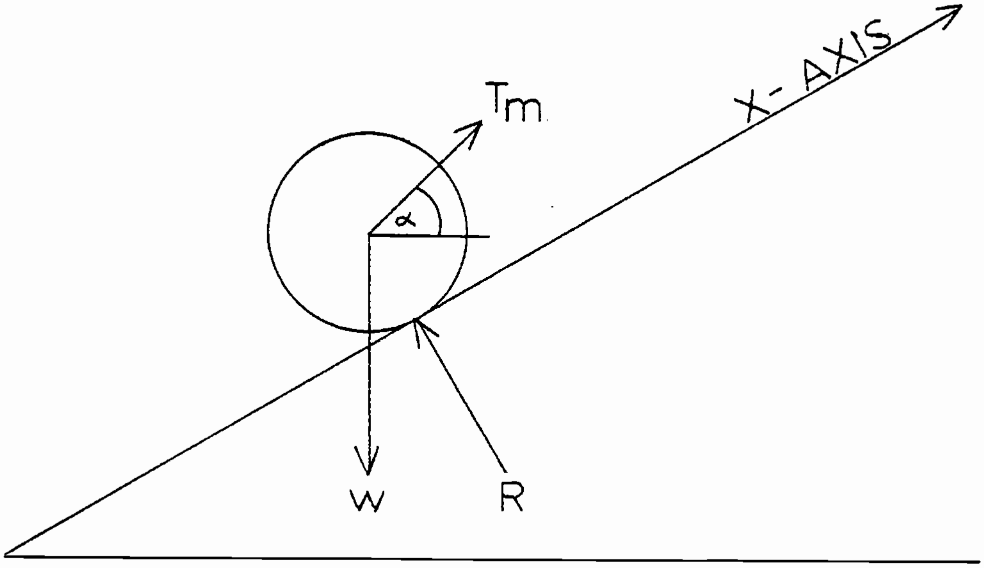


Figure 1
WHEEL ON INCLINED PLANE

A single sheave carriage rolling along a tightly stretched wire cable under the influence of mainline approximates the incline and wheel model as the tension in the cable (Ts) increases. As illustrated by Figure 2, the resultant of the cable tension (analogous to the normal force of the incline plane) must be equal and opposite to the resultant of the combined weight of the sheave and its payload and the mainline tension to hold the sheave in a stationary position on the cable. The mainline tension must exceed this limiting equilibrium tension for the carriage to advance up the cable. This principle of a lower limit for the mainline tension is the first of the necessary conditions that must be satisfied for successful carriage passage uphill over a support jack.

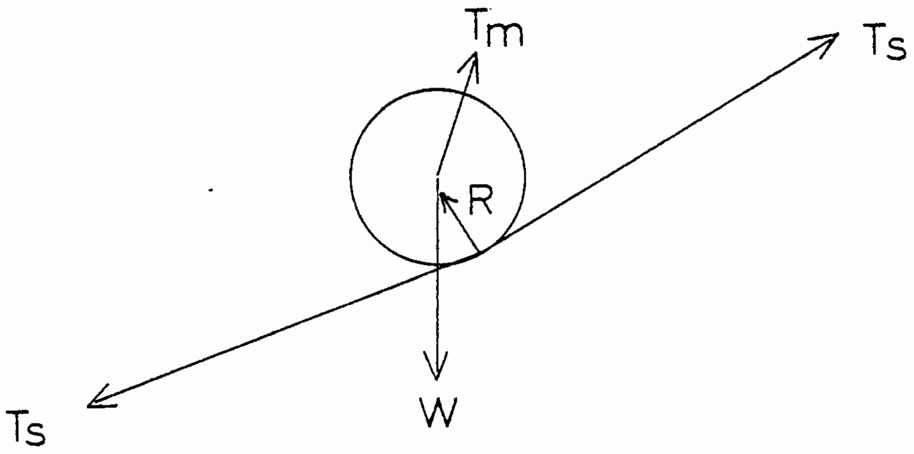


Figure 2
SHEAVE ON TAUT CABLE

Boundary Conditions

As a carriage moves along a skyline, the skyline is deflected in proportion to the resultant of the mainline tension and gross payload (carriage weight and payload) and the amount of tension in the skyline. For a given geometry of the skyline supports and resultant payload-mainline force, this deflection will increase as the skyline tension (Ts) is decreased. Increased deflection is obtained by an increase in skyline length for a given geometry. If the skyline length is increased sufficiently, or equivalently, if the skyline tension is reduced sufficiently, the equilibrium conditions depicted in the free body diagram of Figure 3 are obtained.

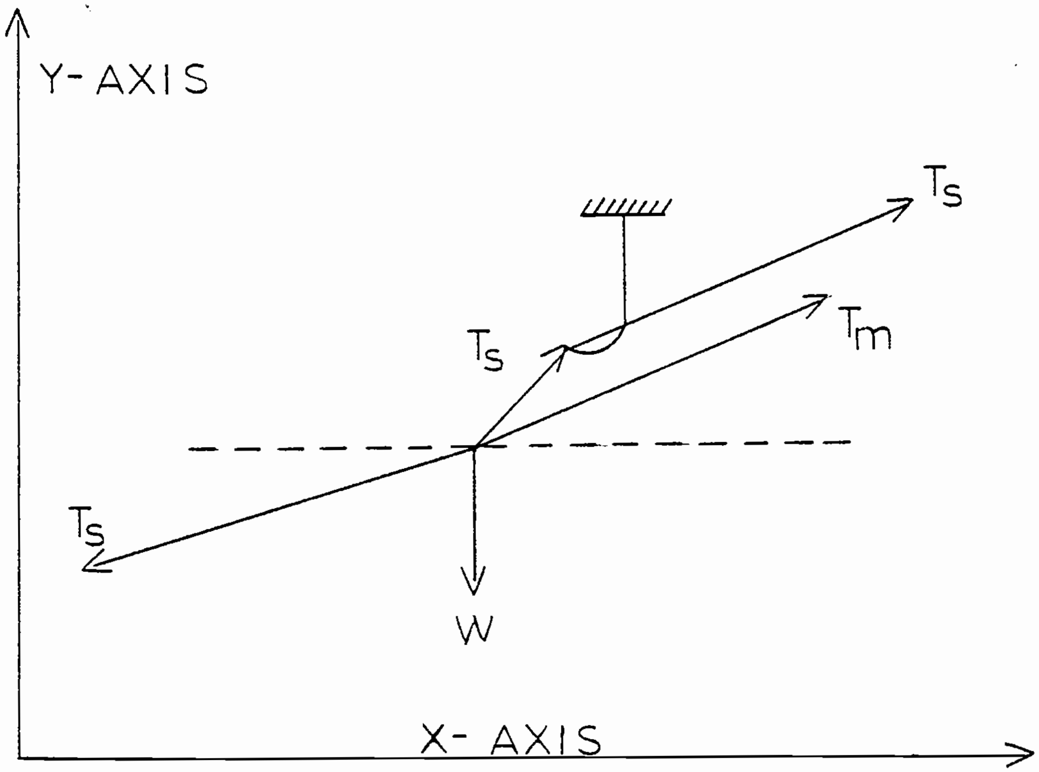


FIGURE 3

CARRIAGE NEAR THE JACK

The carriage will stop until the tension in the mainline is increased above its equilibrium value or its direction of application is changed. With an increase in mainline tension or positive change in direction of application, there is an unbalance of forces and the carriage will move up the skyline until a new equilibrium condition is reached. If the initial skyline length is long enough to establish the equilibrium geometry at the jack as illustrated by Figure 4, then any further increase in mainline tension without a change in its direction of application, would result in the geometry illustrated by Figure 5.

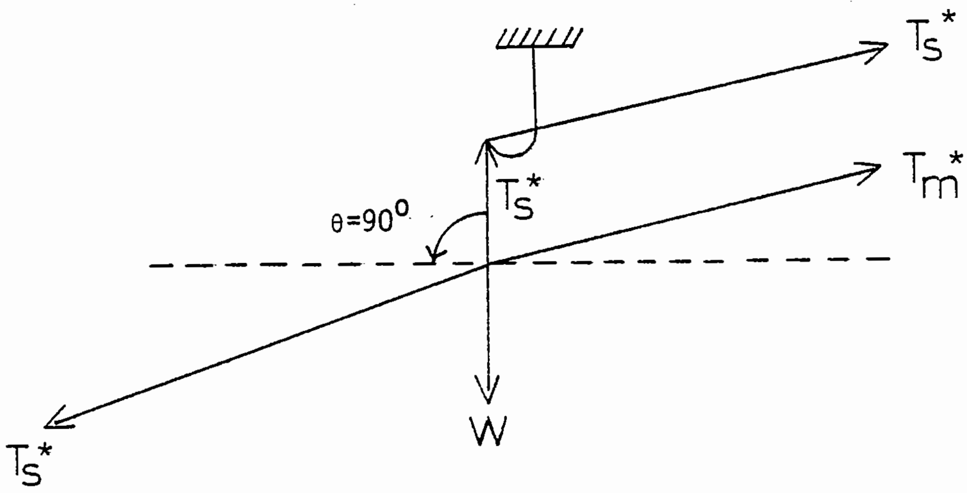


Figure 4

CRITICAL GEOMETRY (θ = 90°)

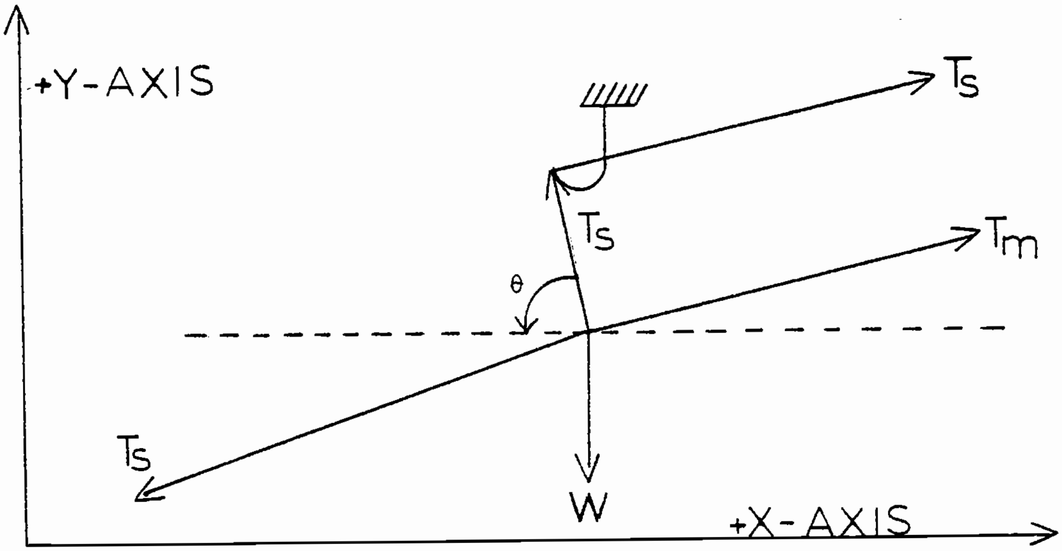


Figure 5

CRITICAL GEOMETRY EXCEEDED ($\theta < 90^0$)

Because the carriage has advanced beyond the jack it is no longer possible for the carriage to successfully pass over the support jack by applying a mainline force to the right. Thus, carriage hang-up at the support jack will occur. Figure 4, therefore, represents the boundary or critical geometry conditions for successful uphill carriage passage. The principle of a critical mainline tension and critical skyline tension are the two boundary conditions upon which the following analyses are based. Predictor equations are developed for critical mainline and skyline tension assuming that cable segments are: (1) weightless, (2) rigid links, and (3) catenaries.

Weightless Line Analysis

The following is a modification of a weightless line analysis (Peters, 1977) to predict the critical conditions for successful carriage passage uphill over an intermediate support jack. This analysis includes the following assumptions:

1. The carriage has negligible dimensions and momentum,
2. Sheaves are frictionless,
3. The support jack is rigid and the initial anchor geometry and payload remain constant,
4. The length of skyline between the support jack and carriage front sheave at critical conditions at the jack is negligible, $(y=0)$,
5. The payload is fully suspended, and
6. Lines are weightless straight links, pin connected at each end.

Geometry:

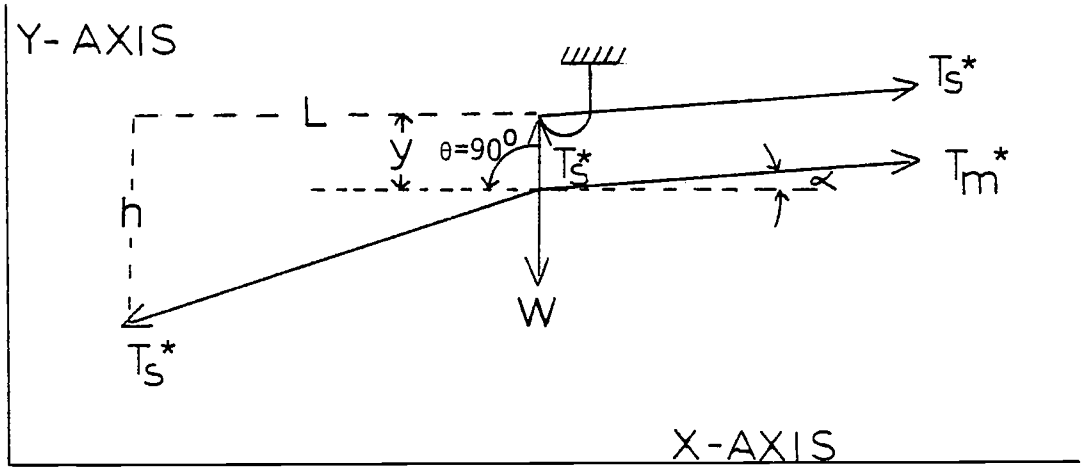


Figure 6

WEIGHTLESS LINE GEOMETRY

Symbols:

L = length of span from support jack to adjacent left downhill anchor point

h = difference in elevation between support jack and adjacent left downhill anchor (positive if left anchor lower than support jack and negative if left anchor higher than support jack)

y = length of skyline between support jack and carriage (negligible dimensions)

Ts* = critical skyline tension

Tm* = critical mainline tension

W = gross payload (carriage weight plus payload weight)

α = angle in degrees, measured as positive counter-clockwise, from the horizontal to the mainline

θ = critical angle of skyline segment between the carriage and the support jack, measured positive counter-clockwise from the skyline to the horizontal and equal to 90°.


= schematic symbol for support jack

Critical mainline tension and critical skyline tension are obtained when equilibrium exists at the jack and $\theta = 90^{0}$. If mainline tension or skyline tension are less than critical, then the carriage will hang up. The equations of equilibrium are now solved for the critical conditions:

$\Sigma Fx = 0$:

$$Tm^* \cos \alpha = \frac{L}{\sqrt{h^2 + L^2}} Ts^* \tag{1}$$

$\Sigma Fy = 0$:

$$Ts^* + Tm^* \sin \alpha = W + \frac{h}{\sqrt{h^2 + L^2}} Ts^* \tag{2}$$

Combine (1) and (2) and solve for Ts*,

$$Ts^* = \frac{W}{[1 - \cos \lambda \, (\tan \lambda - \tan \alpha)]} \tag{3}$$

where $\tan \lambda = \frac{h}{L}$ and $\cos \lambda = L/\sqrt{h^2 + L^2}$

Equation 3 predicts the critical skyline tension that exists for a given geometry and payload. If the skyline tension is less than the critical skyline tension, the carriage will hang-up at the jack. The parameter $(\tan \lambda - \tan \alpha)$ is approximately equal to the chord slope break. The greater the chord slope break, the greater the skyline tension required for a given payload.

In a similar manner, the equations of equilibrium can be solved for mainline tension as a function of geometry and payload to give the following equation:

$$Tm^* = \frac{W \cos \lambda / \cos \alpha}{[1 - \cos \lambda \, (\tan \lambda - \tan \alpha)]} \tag{4}$$

where $\tan \lambda = h/L$ and $\cos \lambda = L/\sqrt{h^2 + L^2}$

Equation 4 predicts the critical mainline tension that exists for a given geometry and payload. If the mainline tension is less than the critical mainline tension, the carriage will hang-up at the jack. Critical mainline tension is also dependent on the magnitude of the chord slope break and will normally be less than the critical skyline tension.

Rigid Link Analysis

The following analysis was developed for predicting the critical conditions at the jack for uphill yarding based upon a rigid link assumption for the lower skyline cable segment (Peters, 1977). This analysis was developed to obtain a better predictor of critical conditions than that provided by the weightless line analysis. The following assumptions are made:

1. Assumptions 1-5 of the weightless line analysis hold,
2. The lower skyline cable segment is a rigid link, pin connected, having a constant weight per unit length, and
3. Second order terms of cable weight divided by skyline tension are negligible.

Geometry:

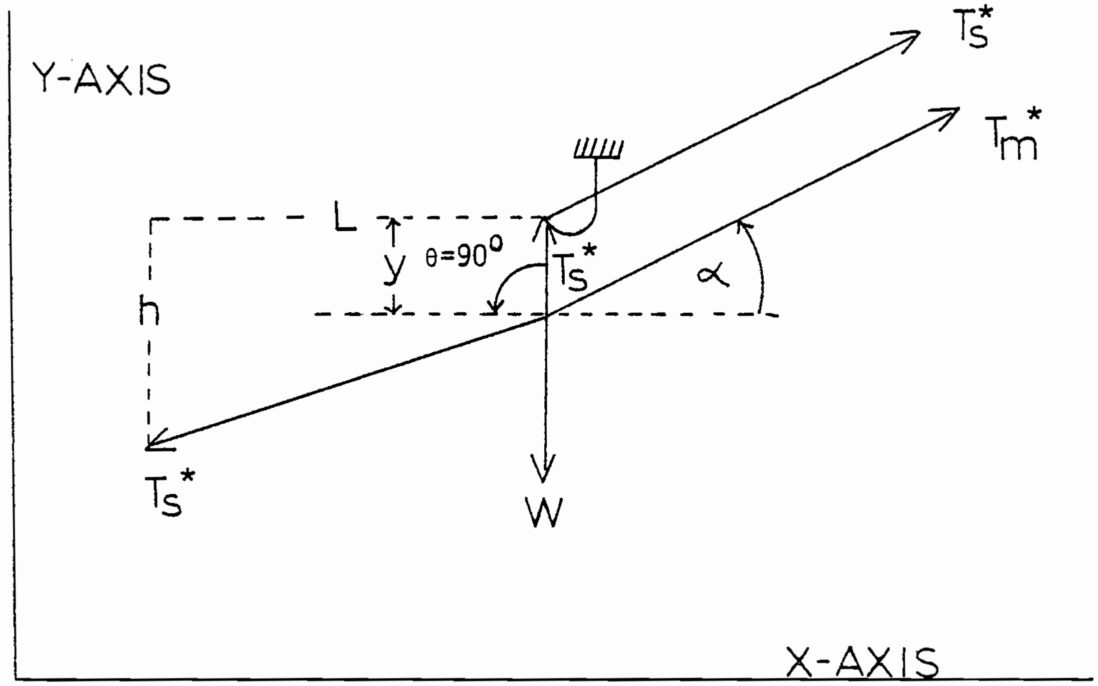


Figure 7

RIGID LINK GEOMETRY

Symbols:

L = length of downhill span from support jack to anchor point
h = difference in elevation between support jack and downhill anchor. (Positive if anchor is lower than support jack and negative if anchor is higher than support jack.)
y = length of skyline between the support jack and carriage, negligible
Tm* = critical mainline tension
Ts* = critical skyline tension
V = vertical component of Ts*
H = horizontal component of Ts*
W = gross payload (carriage weight plus payload weight)
ω = weight per unit length (one foot) of the skyline
α = angle in degrees, measured as positive counter-clockwise, from the horizontal to the mainline
θ = critical angle of the skyline segment between the carriage and the support jack. Measured positive counter-clockwise from the skyline to the horizontal and equal to 90^o

 = schematic symbol for the support jack

Analysis:

Critical conditions at the jack for uphill carriage passage exist when the forces at the jack are in static equilibrium and θ equals 90^0. The equations of equilibrium are solved to determine the critical tensions at the jack. Refer to the free body diagram of Figure 10, where the tension in the lower skyline segment has been replaced by its component parts.

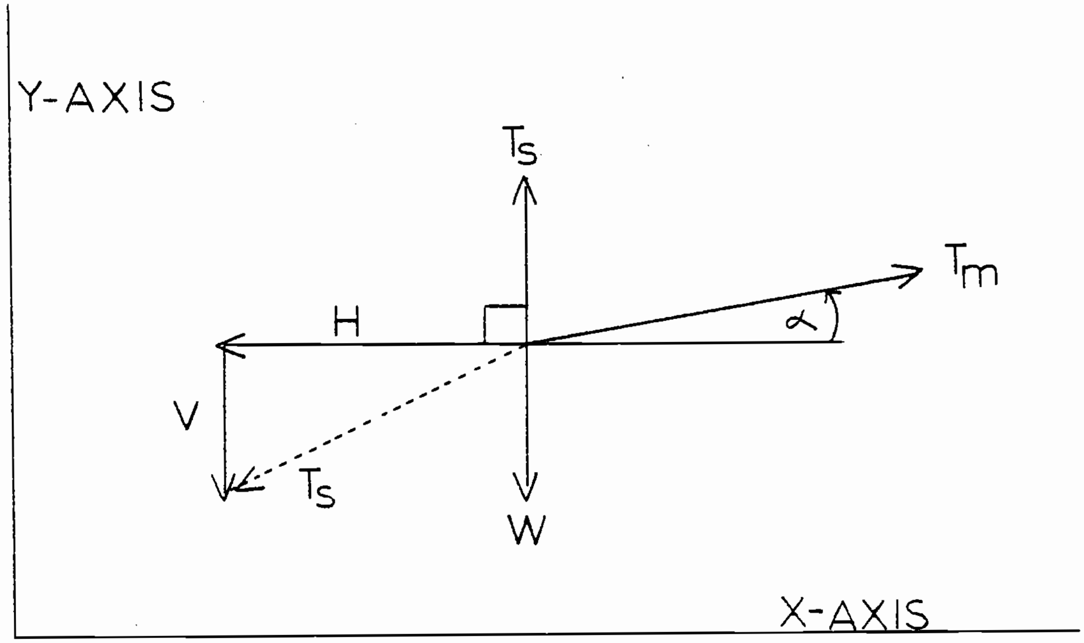


Figure 8

RIGID LINK FORCE BALANCE AT THE JACK

$\Sigma F_X = 0$:

$$Tm^* \cos \alpha = H \tag{5}$$

and,

$\Sigma F_Y = 0$:

$$Ts^* + Tm^* \sin \alpha - W = V \tag{6}$$

To solve for H and V in terms of Ts* and Tm*, an equilibrium equation is written for the lower skyline cable segment (Figure 11). The subscript ℓ refers to the lower cable segment component forces.

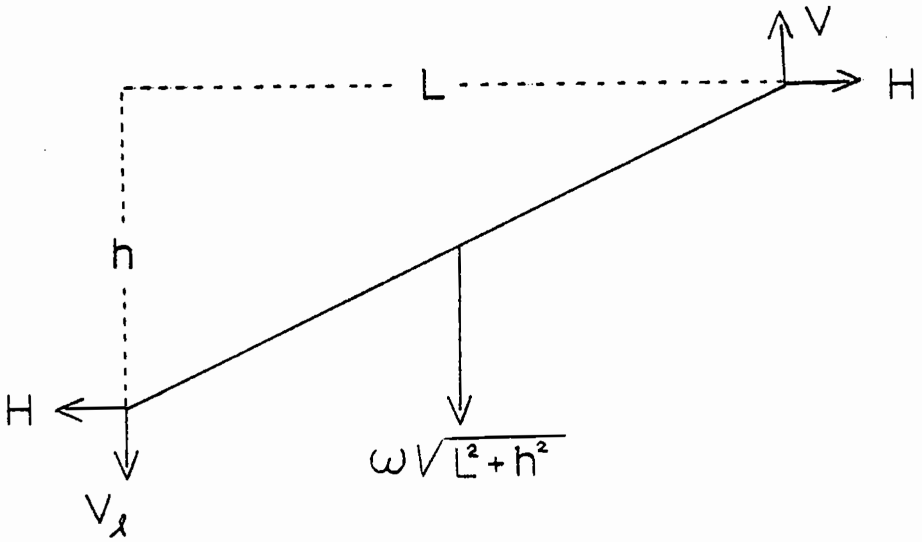


Figure 9

RIGID LINK SEGMENT FORCE BALANCE

Summing moments about the lower cable segment as positive clockwise, the following relationship is obtained:

$\circlearrowright + \; \Sigma M_\ell = 0$:

$$\omega\sqrt{L^2 + h^2}\;\frac{L}{2} + Hh = VL \tag{7}$$

From the Pythagorean theorem, H can be solved for in terms of Ts, ω, h and L as follows:

$$Ts*^2 = V^2 + H^2$$

solve for H^2 and substitute equation 7 for V,

$$H^2 = Ts*^2 - \left[\frac{\omega}{2}\sqrt{L^2 + h^2} + \frac{H\,h}{L}\right]^2$$

$$H^2 = Ts*^2 - \frac{H^2h^2}{L^2} - \omega\sqrt{L^2 + h^2}\;\frac{H\,h}{L} - \frac{\omega^2}{4}\,(L^2 + h^2)$$

$$H^2\left(1 + \frac{h^2}{L^2}\right) + \frac{\omega h}{L}\sqrt{L^2 + h^2}\;H - \left(Ts*^2 - \frac{\omega^2}{4}\,(L^2 + h^2)\right) = 0$$

using the quadratic equation to solve for H,

$$H = \frac{-\frac{\omega h}{L}\sqrt{L^2 + h^2} \pm \sqrt{\left(\frac{\omega h}{L}\sqrt{L^2 + h^2}\right)^2 + 4\left(Ts^2 - \frac{\omega^2}{4}(L^2+h^2)\right)\left(1 + \frac{h^2}{L^2}\right)}}{2\;\left(1 + \frac{h^2}{L^2}\right)}$$

By neglecting terms of magnitude $\frac{\omega^2 L^2}{Ts^2}$ and simplifying, equation 8 is derived:

$$H = (Ts^* - \frac{\omega h}{2}) \frac{L}{\sqrt{L^2 + h^2}} \qquad (8)$$

Combine (7) and (8) to obtain for V,

$$V = (Ts^*h + \frac{\omega L^2}{2}) \frac{1}{\sqrt{L^2 + h^2}} \qquad (9)$$

H from (8) and V from (9) can be substituted into (5) and (6) resulting in two equations in the unknowns, Ts* and Tm*, the critical tensions:

$$Tm^* = (Ts^* - \frac{\omega h}{2}) \frac{L}{\cos \alpha \sqrt{L^2 + h^2}} \qquad (10)$$

and,

$$Ts^* = (Ts^*h + \frac{\omega L^2}{2}) \frac{1}{\sqrt{L^2 + h^2}} - Tm^* \sin \alpha + W \qquad (11)$$

Combine (10) and (11) to obtain an expression for Ts* in terms of known geometry.

$$Ts^* = \frac{W + \frac{\omega L}{2} \cos \lambda \, [1 + \tan \alpha \tan \lambda]}{[1 - \cos \lambda \, (\tan \lambda - \tan \alpha)]} \qquad (12)$$

where

$$\cos \lambda = \frac{L}{\sqrt{L^2 + h^2}}$$

and

$$\tan \lambda = \frac{h}{L}$$

The skyline tension given by equation (12) represents the critical skyline tension for successful carriage passage. If the tension in the skyline is less than this tension, the carriage will not pass the support jack.

In a similar manner, equations 10 and 11 can be solved for the critical mainline tension.

$$Tm^* = \frac{(W \cos \lambda + \frac{\omega L}{2} (1 - \sin \lambda))/\cos \alpha}{[1 - \cos \lambda(\tan \lambda - \tan \alpha)]} \tag{13}$$

Equation 13 predicts the critical mainline tension for a given geometry and payload. If the mainline tension is less than the critical mainline tension, the carriage will hang-up at the jack. Critical tensions predicted by rigid link analysis, (12) and (13), are greater than those predicted by weightless line analysis, (3) and (4), by an additional cable weight term.

Catenary Analysis

For taut cables (cable weight much less than tension), rigid link cable segment analyses give results very similar to catenary analyses. As the cable weight increases in relation to the cable tension, the catenary model better describes the cable system. To obtain a more general method of determining critical tensions for any span length and cable size, the following catenary analysis was developed.

Assumptions:

1. Assumptions 1-5 of the weightless line analysis hold, and
2. Cable segments can be described by catenaries.

Geometry:

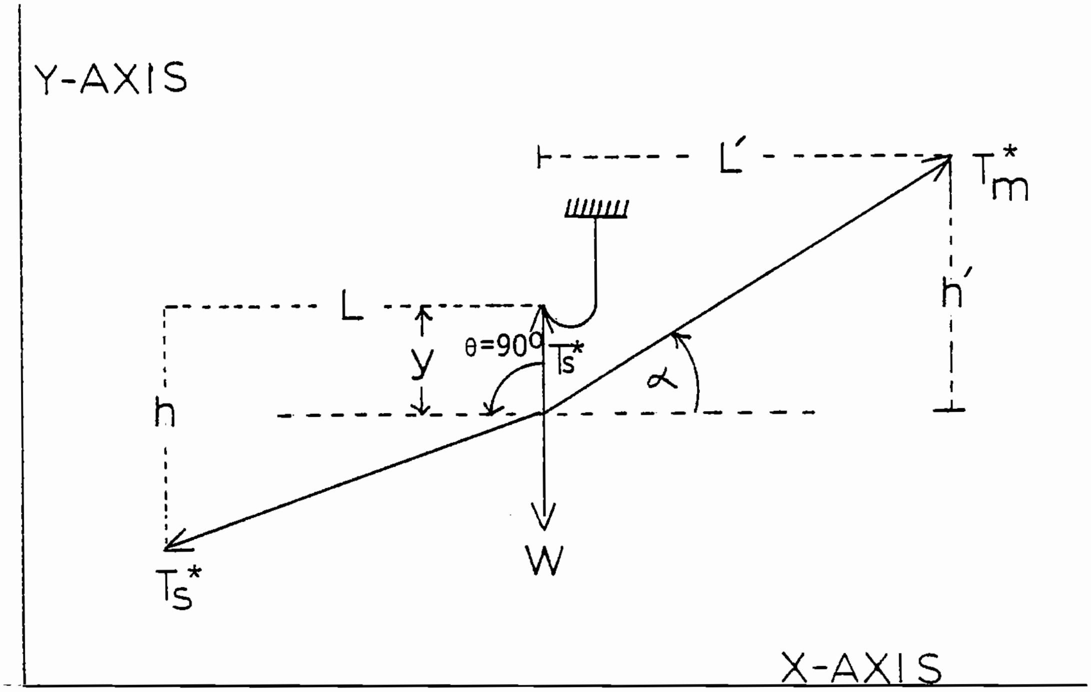


Figure 10

CATENARY GEOMETRY

Symbols:

L = length of downhill span from support jack to anchor point
L' = length of uphill span from the support jack to head spar
h = difference in elevation between the support jack and downhill anchor. Measured as negative if the left anchor is lower than the support jack and positive if the left anhor is higher than the support jack.
h' = difference in elevation between the support jack and head spar Measured as positive if the head spar is higher than the support jack and negative if the head spar is lower than the support jack.
y = length of skyline between the support jack and carriage, negligible
Tm* = critical mainline tension
Ts* = critical skyline tension
V_1 = vertical component of Ts*
H_1 = horizontal component of Ts*
V_3 = vertical component of Tm*
H_3 = horizontal component of Tm*
ΔS_1 = length of skyline cable segment
ΔS_3 = length of mainline cable segment
e_1 = the lever arm from the lower end of skyline cable segment to its center of gravity

e_3 = the lever arm from the lower end of mainline cable segment to its center of gravity
W = gross payload (carriage weight plus payload weight)
ω_1 = weight per unit length of the skyline
ω_3 = weight per unit length of the mainline
m_1 = catenary parameter for skyline cable segment, $m_1 = \frac{H_1}{\omega_1}$
m_3 = catenary parameter for mainline cable segment, $m_3 = \frac{H_3}{\omega_3}$
α = angle in degrees, measured as positive counter-clockwise, grom the horizontal to the mainline
θ = critical angle of the skyline segment T measured positive counter-clockwise from the skyline to the horizontal and equal to 90°
 = schematic symbol for the support jack

Analysis:

The boundary conditions that describe critical conditions at the jack for uphill carriage passage are the same as in the weightless line and rigid link analysis. The forces at the jack are in static equilibrium and θ equals 90°. Catenary equations and the equations of equilibrium have been solved by iteration to determine critical tensions for carriage passage over the support jack.

The catenary expressions for cable segment length and lever arm are (Carson, 1977):

$$\Delta S = \sqrt{h^2 + \left[2m \sinh\left(\frac{L}{2m}\right)\right]^2} \tag{14}$$

and

$$e = \frac{L}{2} + \frac{mh}{\Delta S}\left[\frac{L}{2m}\coth\left(\frac{L}{2m}\right) - 1\right] \tag{15}$$

Equation 16 is derived from the free body diagram of the cable segment, Figure 11. Subscript "u" refers to the upper end of the cable segment.

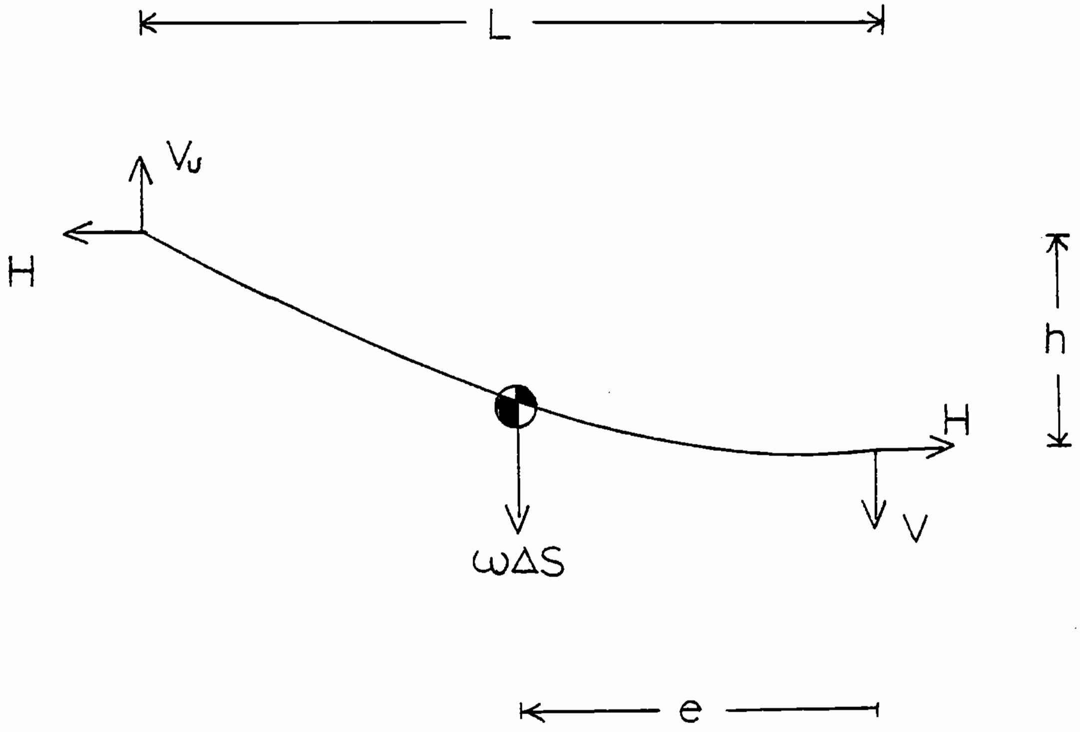


Figure 11

CATENARY SEGMENT FORCE BALANCE

Summing moments about the upper segment, where clockwise rotations are positive:

$$\circlearrowright\!\!+ \; M_U = 0$$

$$\omega\Delta S\ (L - e) + VL = Hh$$

solving for V,

$$V = \frac{Hh - \omega\Delta S\ (L - e)}{L} \tag{16}$$

Two additional equations of equilibrium can be determined by reference to Figure 12 . They are:

$$H_1 = H_3 \tag{17}$$

and

$$Ts^* + V_3 - V_1 = W \tag{18}$$

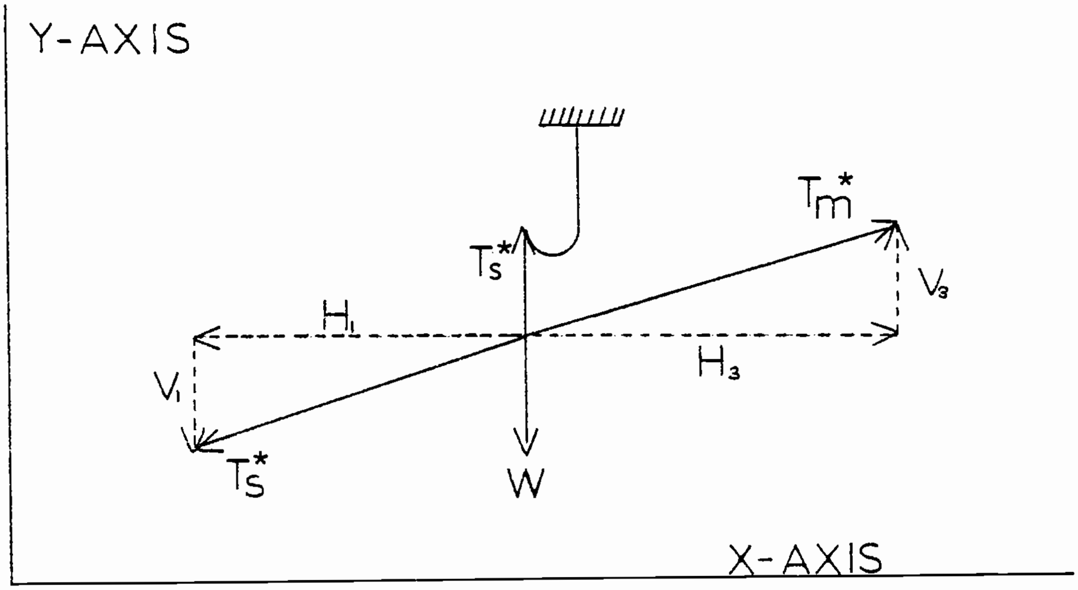


Figure 12

CATENARY FORCE BALANCE AT THE JACK

Using the above equation, an iterative procedure can be used to solve for the critical tensions. Begin by assuming that the horizontal force of the skyline is equal to the gross payload, i.e., $H_1 = W$. Then solve for m_1, where;

$$m_1 = \frac{H_1}{\omega_1}$$

Calculate ΔS_1 and e_1 and obtain the vertical component of the skyline tension at the carriage, V_1. From the Pythagorean theorem, Ts* can now be determined as

$$Ts^{*2} = H_1^{\,2} + V_1^{\,2}$$

Set $H_3 = H_1$ and calculate V_3 and Tm*. If the initial assumption for H_1 was correct, the net vertical force of the cables will equal the gross payload. Let

$$\tilde{W} = Ts^* + V_3 - V_1,$$

if $\tilde{W} \neq W$

then adjust H_1 as follows:

$$\tilde{H}_1 = H_1 \frac{\tilde{W}}{W}$$

where $\tilde{H}_1$ is the new estimate for H_1. The same procedure is repeated with the new H_1 estimate until $\tilde{W} = W$, signifying that equilibrium exists at the jack. Ts* and Tm* under equilibrium conditions represent the critical tensions for successful carriage passage over the support jack. The iterative procedure has been described by the flow chart in Figure 13. A Hewlett Packard 67 computer program used in the solution is listed in Appendix A.

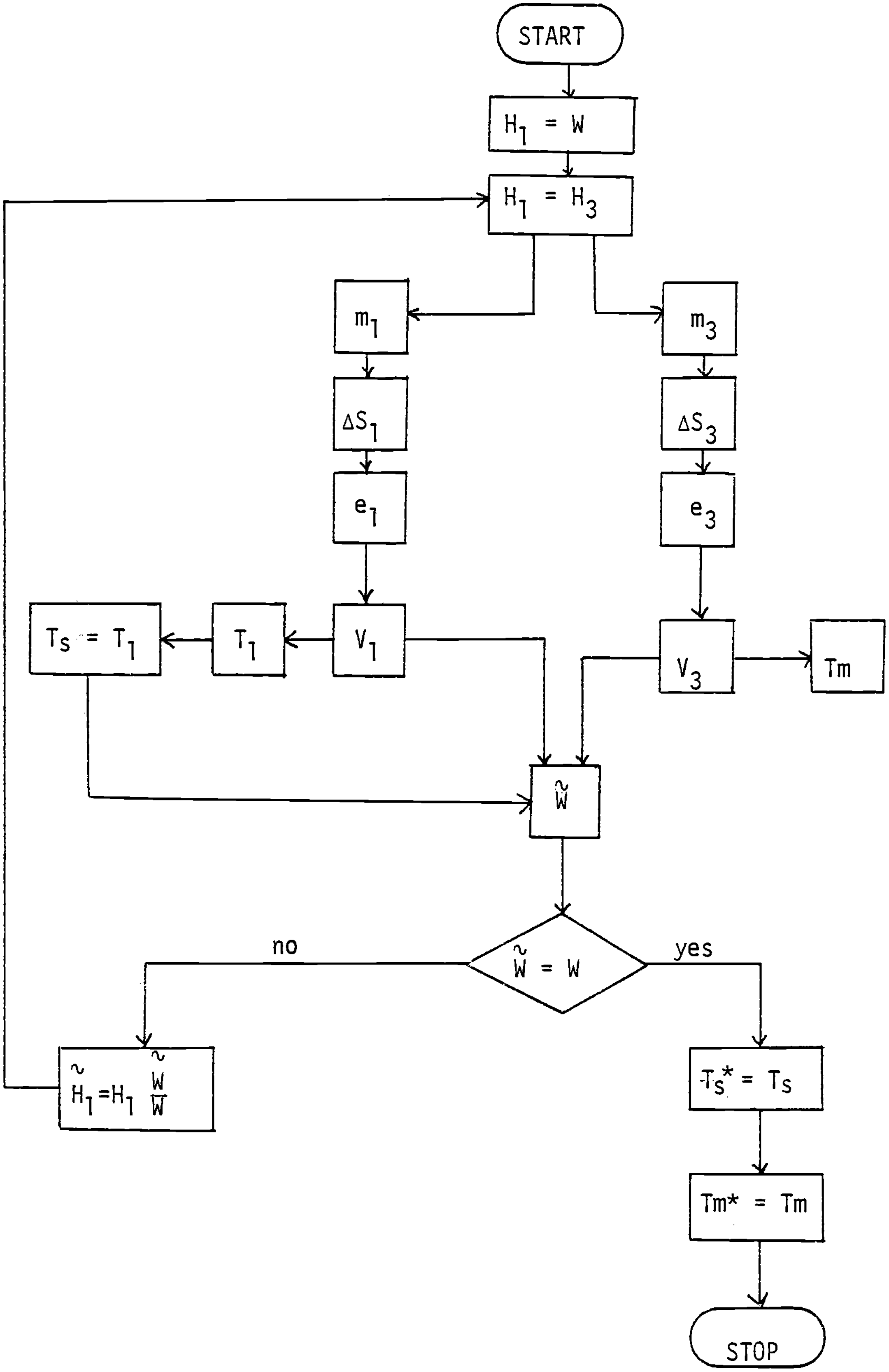


FIGURE 12
CATENARY SOLUTION FLOW CHART

IV. DESCRIPTION OF FIELD TEST

Purpose of Test

Prior to the field test, Peters (1977) had formulated a weightless line analysis to describe the critical conditions for successful carriage passage uphill over an intermediate support jack. The field test was designed to either validate this analysis or obtain empirical data that could be used in the design phase of multispan skyline layout to predict carriage passage.

Discussion of Parameter Selection

From the original weightless line analysis, it was concluded that carriage passage at the jack for uphill yarding was a function of the following parameters: tension in the mainline, Tm*, the angle of pull at the carriage of the mainline, α, gross payload, W, and the span geometry, L and h. During subscale model testing, it was also observed that the length of the skyline, or equivalently skyline tension, was an important factor in determining successful carriage passage. A fixed gross payload, W, was used throughout the field test for convenience. Time and economics limited us to selecting three yarding geometry configurations. For each test run, the skyline length, as measured by midspan deflection, was varied and mainline and skyline tensions recorded. The position of the support jack was not fixed, as is common in most multispan logging operations. We measured its position when the gross load was at the jack in order to establish the actual geometry during carriage passage or hang-up. Thus, for each test run, the values for all the important parameters thought to influence carriage passage were recorded.

Test Equipment

Ground profiles of all three test sites were run using a 100-foot steel chain and abney. Slope percent was measured to the nearest one-half percent and slope distance to the nearest one-tenth foot. Two T 60-D theodolites and a 100-foot steel chain were used to determine the height of the tail tree and jack supports as well as support jack movement during the test. The vertical distance from the top of the mainline sheave to the ground was measured with a 50-foot loggers steel tape to the nearest one-tenth foot. During the test runs, mid-span deflection was determined from horizontal and vertical angles measured with one of the theodolites. All theodolite measurements were read to the nearest one-half minute. Skyline tension was measured using a Martin-Decker UB2 tension indicator, which was precalibrated before the tests, and clamped to the skyline near the tail hold. Readings were recorded to the nearest one-hundred pounds with a possible instrument error of ± 3%.

The mainline tension was measured using a continuous recording Dillon tension load cell attached by shackle to the mainline about five feet from the carriage. Readings were recorded to the nearest one-hundred pounds with a possible instrument error of ± 1.03%. The yarder used for all three tests was a Schield-Bantam T 350, 100 h.p. mobile yarder, rigged with 3/4" skyline, 5/8" mainline, and 7/16" haulback. A 1700 pound concrete block secured to a SKA 2 Automatic

Koller carriage weighing 590 pounds, served as the payload. Both carriage and concrete block were pre-weighed using a Dillon 5000 pound capacity scale. The support jack used was a Koller 2.5 ton, two piece support jack. Two-way voice radios were used to communicate yarder commands to the yarder operator. Appendix B contains a complete listing of test equipment with specifications.

Crew

Pre-test surveying and rigging were accomplished by a two-man crew while a five-man crew was required throughout the actual testing. For each run, one man monitored the mainline tension recordings; two men manned the midspan and support jack theodolite stations; one man monitored the tailhold skyline tension gauge; and, the fifth crew member operated the yarder.

Pre-test Design

In order to test and compare a broad range of conditions, profiles were selected that would require both sharp and moderate chord slope breaks. Figures 14, 15, and 16 show the selected profiles and their initial geometry for tests one, two, and three respectively. Ground profile coordinates can be found in Appendix E for each test.

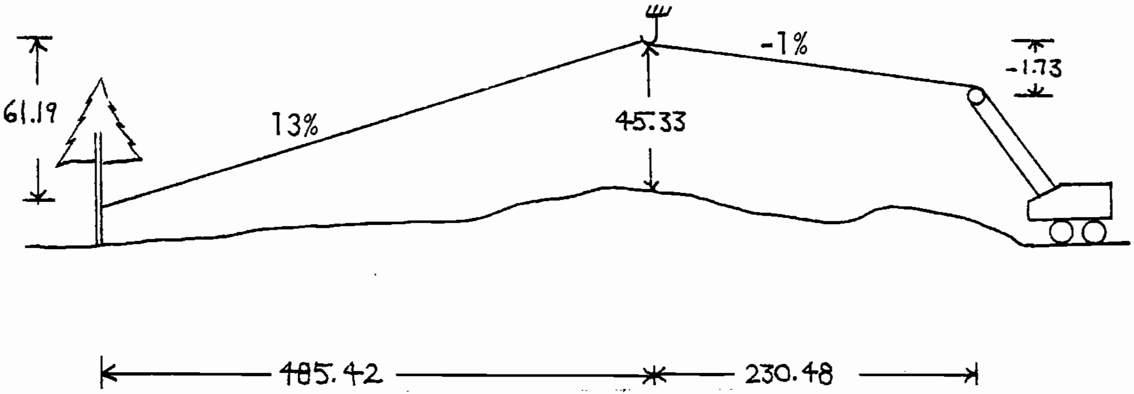


Figure 14

TEST ONE INITIAL GEOMETRY

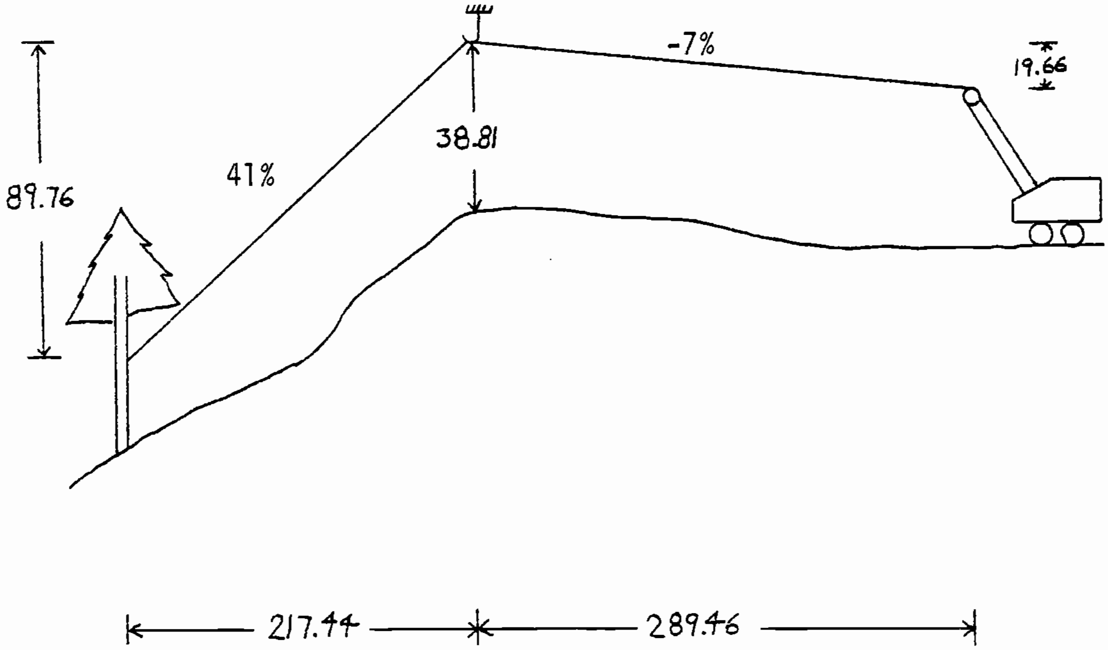


Figure 15

TEST TWO INITIAL GEOMETRY

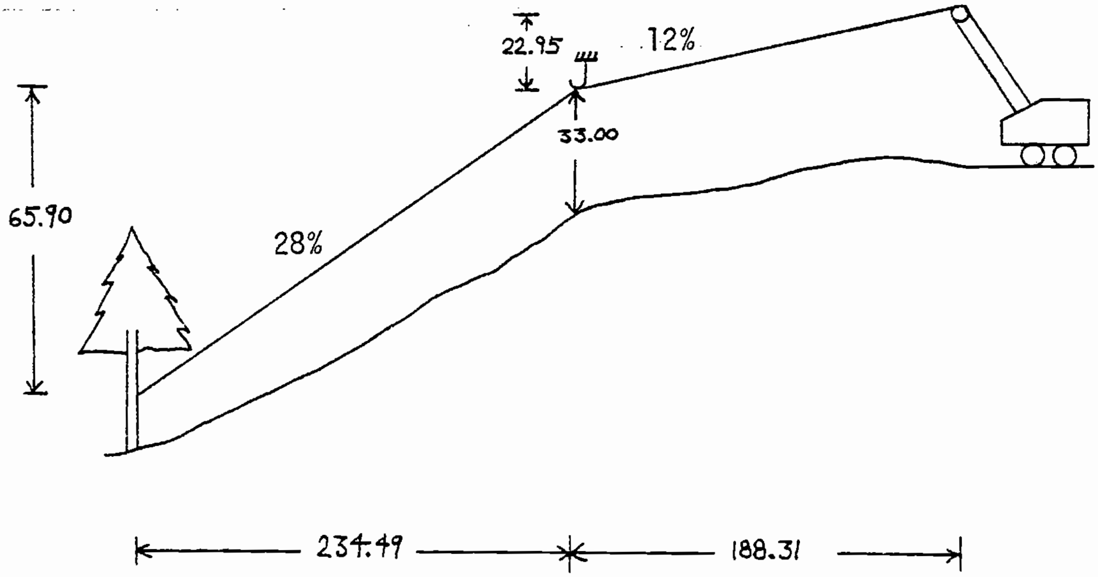


Figure 16

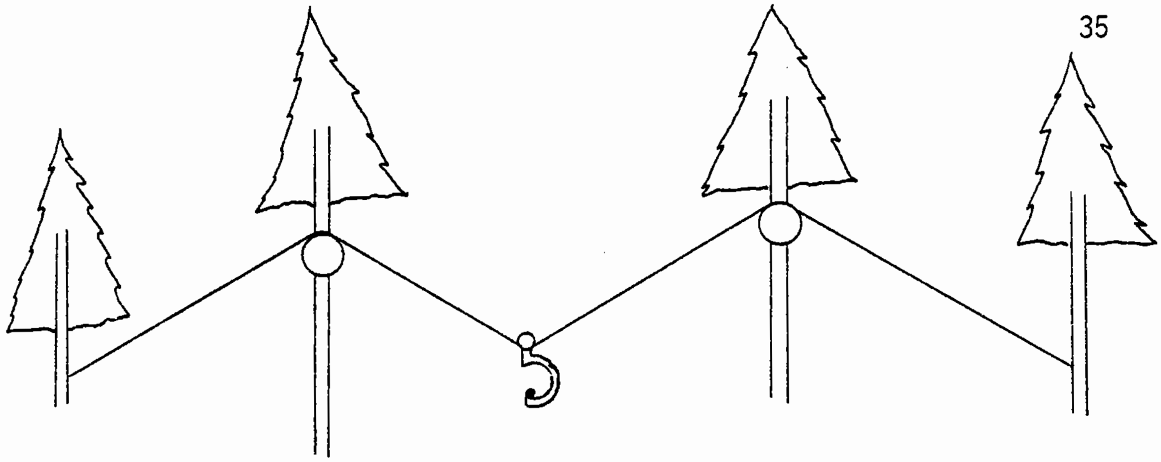
TEST THREE INITIAL GEOMETRY

Test Procedure

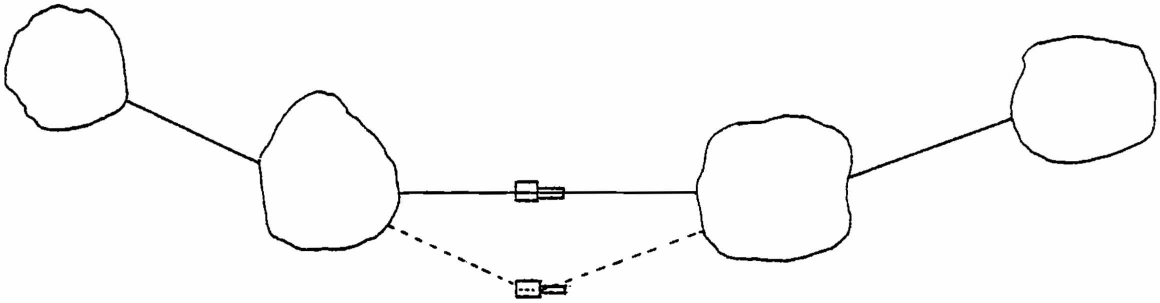
Figure 17 below illustrates the method of rigging the intermediate support trees as utilized throughout the three test settings. A block was hung in each intermediate support tree. A single line was passed through these blocks and the support jack and tied off to a tree at both ends.

Note that the jack support line is guyed back, anticipating some forward movement of the jack during skyline tensioning and yarding.

After each test setting was rigged, the mainline height and tail tree support height were measured. One theodolite was then set up a convenient distance perpendicular to the skyline corridor at midspan. The second theodolite was positioned a convenient distance perpendicular to the skyline corridor at the support jack. The static skyline tension gauge was clamped to the skyline near the tailhold, and the continuous mainline tension recorder was located near the base of the intermediate support trees.



Front View



Top View

Figure 17

TEST RIGGING

The steps for obtaining the measurements recorded for each run were:

1. The carriage was positioned as close to the jack as possible without passing over the jack. With the carriage in this position, the static tension in the mainline and skyline were recorded. The horizontal and vertical angles to the jack were turned and recorded to determine both the vertical and horizontal displacement of the jack. Using the horizontal displacement, the new span length between jack and tail support was computed. Based on this new span length, the angle to turn from the initial midspan station to the

new midspan location was computed and turned.

2. The carriage was next statically positioned at the established midspan location, where the vertical angle from the ground at midspan to the skyline was turned and recorded, thus midspan deflection could be calculated. The tension in the skyline was also recorded. Due to a limited length of electrical cable, mainline tension was not measured at midspan.
3. The carriage was next yarded to within one-hundred feet of the support jack where the mainline tension cell electrical cable was connected to the recorder. The carriage was then yarded at normal operating speed, up and over the support jack. The minimum skyline tension observed at the tailhold gauge for the run was recorded as the dynamic skyline tension with the carriage at the jack. The maximum recorded mainline tension for the run was recorded as the dynamic mainline tension with the carriage at the jack.
4. After each run, the carriage was positioned near midspan and the skyline was lengthened or slackened to achieve approximately one percent deflection increments. Steps 1 through 3 were then followed until an unsuccessful carriage passage was observed. An unsuccessful passage was defined as either a rough carriage passage or actual hang-up. In Test 1 and Test III, the carriage front or rear sheave came off the skyline after carriage passage over the jack for the limiting run. In Test II, carriage passage was exceedingly rough and the segment of the skyline between the carriage and the jack just prior to passage was nearly vertical, $\theta = 90^0$.

Summary of Data

A complete record of field test data is included in Appendix C. Tables 1, 2, and 3 are summaries of the field test data for tests 1, 2, and 3, respectively.

TABLE 1

TEST ONE FIELD DATA

Run No.	Static T_s[1] at Jack	Static Tm[1] at Jack	α (%)	d (%)	chord slope (Left-Span)(%)	chord slope break(%)
1	19200	500	-.75	3.0	12.61	13.36
2	14500	500	-.72	3.7	12.61	13.33
3	10900	500	-.72	4.3	12.62	13.34
4	6700	700	-.77	5.2	12.63	13.40
5	3600	1600	-1.30	6.7	12.76	14.06
6[2]	3000	2300	-1.69	7.8	12.89	14.58
7[3]	3300	1900	-1.40	7.2	12.79	14.19

1/ Measured in pounds-force.

2/ No dynamic run attempted -- statically it appeared that critical conditions had been exceeded.

3/ Critical run.

TABLE 2

TEST TWO FIELD DATA

Run No.	Static T_s[4] at Jack	Static Tm[4] at Jack	α (%)	d (%)	chord slope (Left-Span)(%)	chord slope break(%)
1	15600	1700	-6.79	4.6	41.28	48.07
2	10300	1400	-6.90	6.2	41.42	48.32
3	6500	2000	-7.12	7.1	41.43	48.55
4[5]	4900	3200	-7.69	9.1	41.58	49.27

TABLE 3

TEST THREE FIELD DATA

Run No.	Static T_s[4] at Jack	Static Tm[4] at Jack	α (%)	d (%)	chord slope (Left-Span)(%)	chord slope break(%)
1	10900	900	12.19	4.3	28.10	15.19
2	6300	1100	12.21	5.7	28.23	16.02
3	4700	1200	12.08	6.3	28.32	16.24
4	3800	1500	12.24	7.1	28.14	15.90
5	3300	1700	12.22	7.7	28.14	15.92
6[5]	2800	2100	11.83	8.7	28.30	16.47

---

[4] Measured in pounds-force.

[5] Critical run.

Although both static and dynamic skyline tensions were measured for each run, static values are thought to be more reliable because of the difficulty that was encountered in interpreting the vibrating gauge needle during dynamic runs. To be consistent, static measured mainline tensions were used in the analysis comparison even though dynamic tensions agreed more closely with analysis predicted tensions. Both static and dynamic measured tensions have been included in the test data in Appendix C.

V. DISCUSSION OF RESULTS

During the field tests, skyline and mainline tensions were measured as midspan deflection was increased for each run until critical conditions at the jack were observed. Midspan deflection was selected as an indirect indicator of skyline length and tension because of its importance as a variable in determining skyline load carrying capacity. However, the theoretical analyses, presented in Section III, predict critical conditions directly in terms of tensions instead of in terms of a critical midspan deflection. Therefore, the principal comparison is between critical skyline and mainline tension as measured in the field test and critical skyline and mainline tension as predicted by catenary, rigid link, and weightless line analyses. This comparison is shown in Table 4.

TABLE 4

FIELD TEST AND ANALYSES COMPARISON (TENSIONS IN POUNDS)

Test Number	T_s^*, Field Test	T_s^* Catenary	T_s^* Rigid Link	T_s^* Weightless	Tm*, Field Test	Tm* Catenary	Tm* Rigid Link	Tm* Weightless
1	3300±750[6]	3053	2958	2665	1900±515[6]	2987	2902	2644
2	4900±750	4581	4391	4202	3200±515	4206	4022	3861
3	2800±750	2947	2866	2721	2100±515	2812	2744	2637

[6] Maximum instrument error, section VI

The predicted skyline tension for each analysis was within the range of field measured values. The catenary model showed the best agreement with the test data. Since it required the least assumptions, it appeared to be the best model for predicting the minimum skyline tension for successful carriage passage uphill over an intermediate support. However, Figure 18 which depicts the predicted skyline tension to payload ratio as a function of downhill span chord slope, for test 1 conditions illustrated that there was reasonably good agreement between all three analyses.

Figure 19 shows the skyline tension at the jack as a function of midspan deflection for the three field tests. As the deflection and line length increased, the skyline tension decreased rapidly at low deflections, then at a greatly reduced rate as the deflection approached the critical value. This indicates that the skyline tension is not extremely sensitive to line length or midspan deflection near the critical condition. Thus, if the conditions observed in the field were not exactly critical ($\theta = 90^{o}$), one would not expect a significant difference between the observed and actual critical skyline tension.

Note, too, that test 1 data agree closely with test 3 data. Test 1 and 3 had nearly the same break in chord slope at the jack, 13% and 16%, respectively.

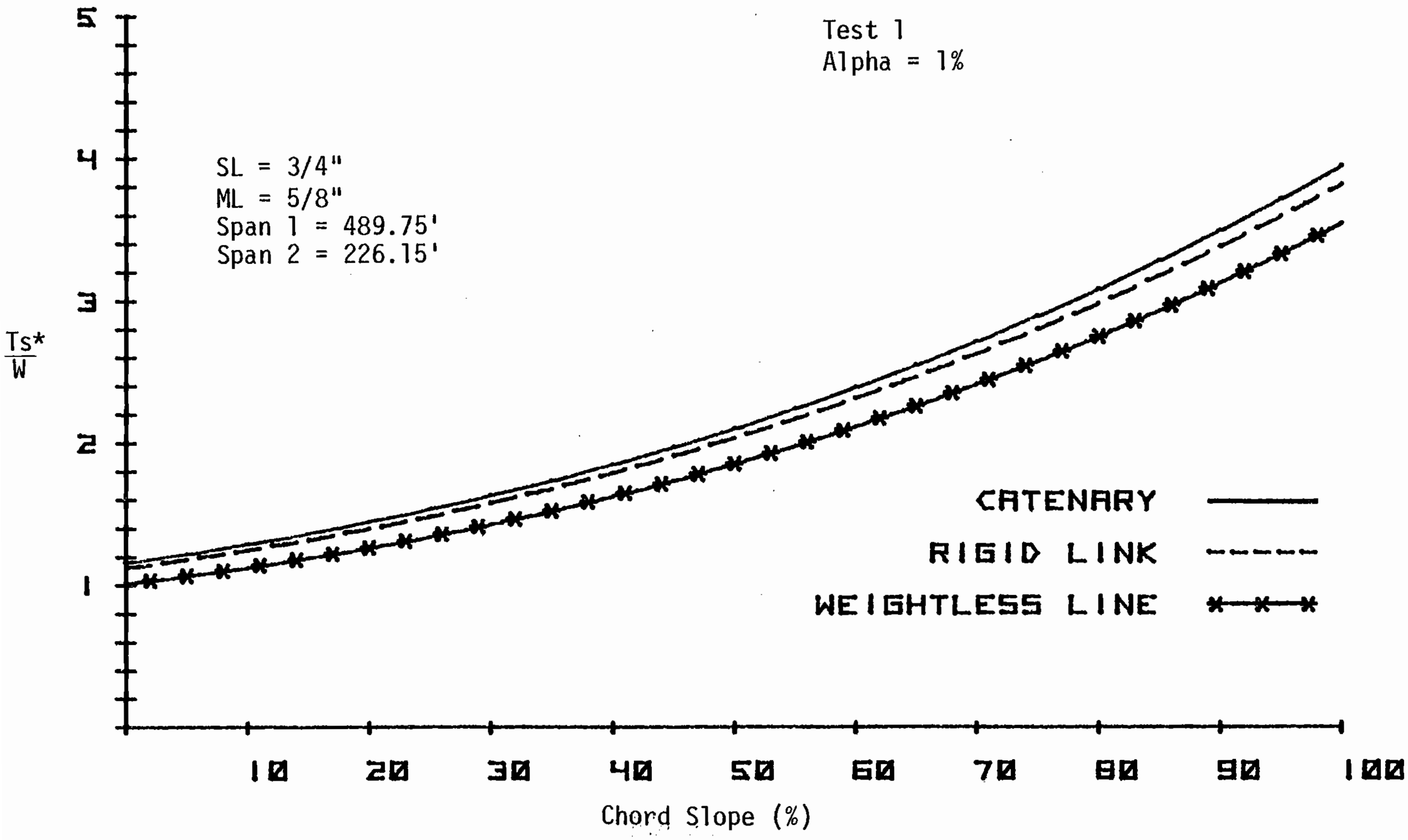


Figure 18

CRITICAL SKYLINE TENSION COMPARISON FOR WEIGHTLESS LINE, RIGID LINK, AND CATENARY ANALYSIS

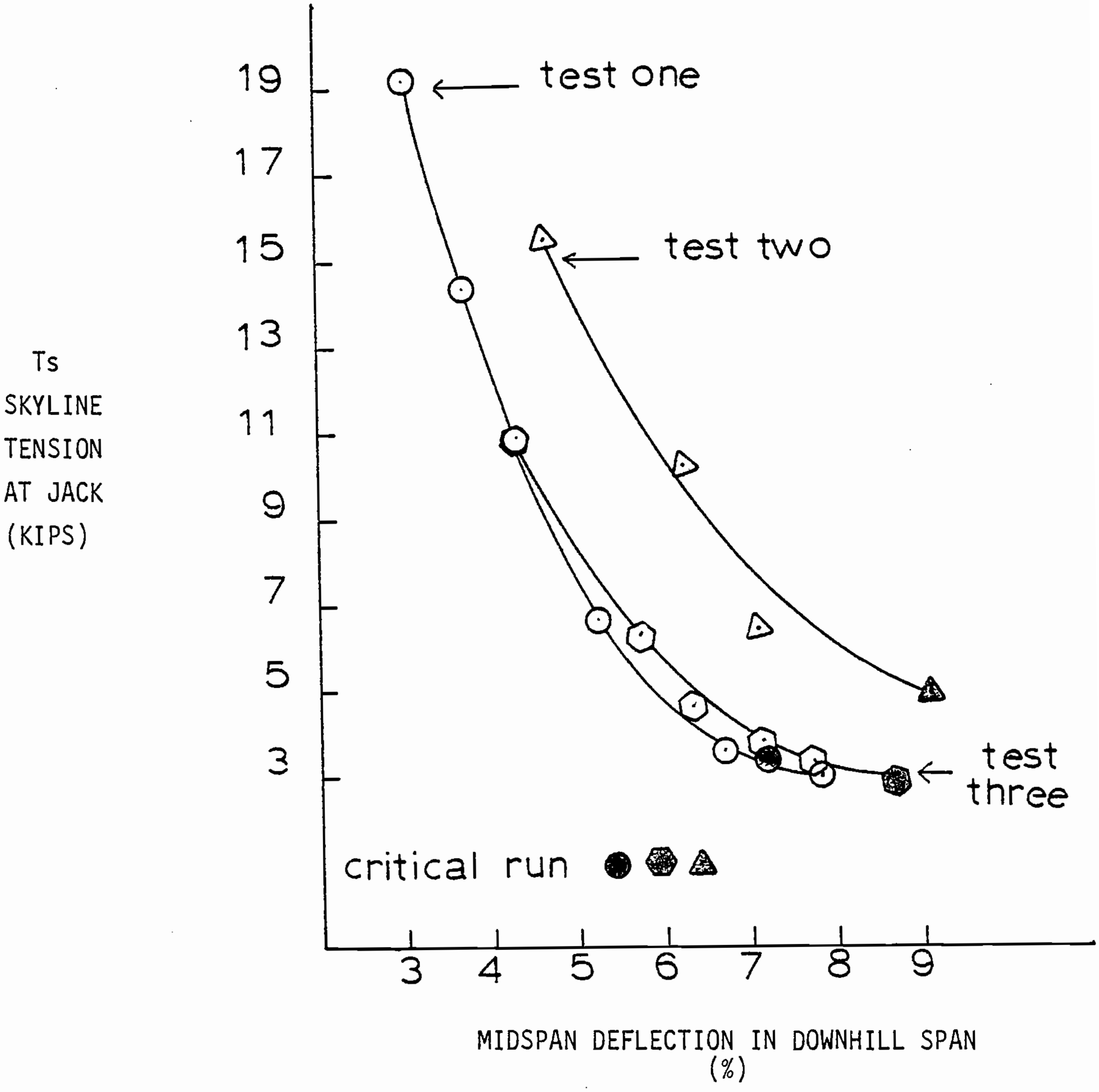


FIGURE 19

SKYLINE TENSION AS A FUNCTION OF DEFLECTION

A comparison of field measured and predicted mainline tensions was not as favorable as the skyline tension comparison.[7] Table 4 shows that none of the analyses values are within the range of static field measured values. The predicted values were consistently above the field values by 700 to 1000 pounds.

Mainline tension as a function of deflection was plotted in Figure 20 for the three field tests. Mainline tension increased quite rapidly as critical conditions were approached (midspan deflection increased). This characteristic is opposite to skyline tension which decreased as critical conditions were approached (Figure 19). If the field observed critical conditions were somewhat in error (θ actually less than 90°), then a lower mainline tension would have been measured. It is likely that safety and prudence biased the field observations on the conservative side. That the carriage actually passed the jack in every critical case substantiates this. While the analysis for critical mainline tension cannot be completely verified from the test results, the consistent and conservative predictions of mainline tension give credence to their usefulness in multispan design.

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[7] Within the range of instrument error, dynamic field measured mainline tensions agreed with the catenary and rigid link analyses predicted tensions for Test 2 and 3. However, to avoid being inconsistent and to maintain a conservative position, static tensions were used throughout the comparison.

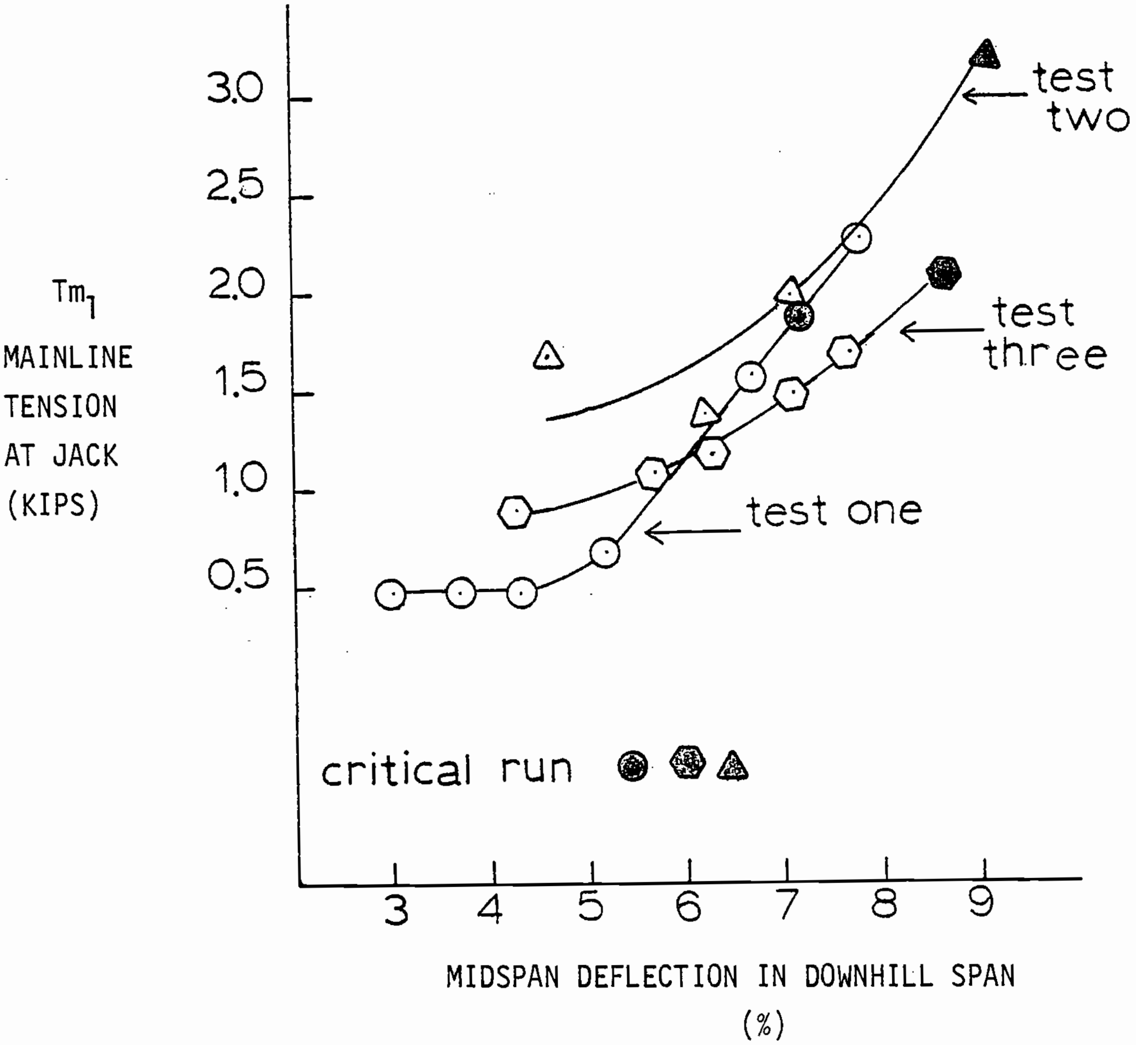


FIGURE 20

MAINLINE TENSION AS A FUNCTION OF DEFLECTION

VI. ERROR ANALYSIS

The following error and sensitivity analysis was undertaken to determine the sensitivity of the parameters in the catenary analysis to measurement errors, and to determine the possible error in the test results. The prediction analysis parameters are considered first.

Prediction Parameters

In the catenary analysis, the critical skyline and mainline tensions are a function of geometry, cable weight, and payload. The initial profile was surveyed with a steel chain and abney. The profile traverses were not closed and adjusted for error. However, because of their short length and the care with which the survey was conducted, it is unlikely that any serious errors were present. It was assumed that profile length and slope measurement errors were random and compensating. The cable weight has a minor effect on the skyline or mainline tension, especially for short spans as in the three tests. Its error was not considered significant. The method of estimating uncertainty as presented by Kline and McClintock (1953) was followed to determine the combined effects of error due to length and angle measurements. The details of the analysis are presented in Appendix D for Test 1. A summary is presented in Table 5.

TABLE 5

PARAMETER ERROR

Parameter	Uncertainty
L_1	± .05 feet
L_3	± .09 feet
h_1	± .08 feet
h_3	± .09 feet
W	± 10 pounds

Lengths were measured to the nearest 0.1 foot and angles to the nearest one-half minute, resulting in respective uncertainties of ± .05 feet and ± 15 seconds. The payload uncertainty was determined by comparison between a certified truck scale weight and Dillon 5000 pound capacity scale.

The sensitivity of the skyline tension to error was evaluated by incrementing lengths by one foot and weight by 100 pounds. Table 6 summarizes these new calculated skyline tensions.

TABLE 6

PARAMETER ERROR SENSITIVITY

Parameter Incremented	Normal Ts* (lbs)	New Ts* (lbs)	Δ Ts* (lbs)
L_1	3052.58	3052.28	0.30
L_3	3052.58	3052.78	-0.20
h_1	3052.58	3045.62	6.96
h_3	3052.58	3037.29	15.29
W	3052.58	2936.17	116.41

A field measured length error two orders of magnitude greater than its combined error would not have a significant effect on the predicted skyline tension value. An error in weight measurement one order of magnitude greater than its actual error would not result in a significant change in tension. Thus it appears that while skyline tension is most sensitive to weight errors, none of the actual parameter errors has a significant effect on predicted values.

Field Results

The skyline and mainline tensions were field recorded using a Martin-Decker UB2 tension indicator and Dillon remote indicating electronic load cell with Rustrak DC Recorder. Using the manufacturer's recommended specifications (Appendix B), the range of instrument error for the skyline tension was determined to be:

$$\text{ERROR} = \pm 3\ \%\ \text{full scale}$$
$$= \pm .03\ (25{,}000\ \text{lbs})$$
$$= \pm 750\ \text{lbs}$$

For the mainline tension, the load cell and recorder error were combined to produce a total possible percent error of:

$$\%\ \text{ERROR} = \sqrt{(1/4)^2 + (1)^2} = 1.03\%$$

From which the range of instrument error for the mainline tension was determined to be:

$$\text{ERROR} = \pm 1.03\%\ \text{full scale}$$
$$= \pm .0103(50{,}000\ \text{lbs})$$
$$= \pm 515\ \text{lbs}$$

Applying these errors to the field data for test 1 at critical conditions resulted in the following values for critical skyline and mainline tensions:

T_s^* : $3300 + 750 = 4050$ lbs

$3300 - 750 = 2250$ lbs

Tm^*: $1900 + 515 = 2145$ lbs

$1900 - 515 = 1385$ lbs

These values represent the maximum possible range of instrument error.

To compare the catenary analysis predictions with the skyline tensions recorded from the field test, the prediction parameters were evaluated at their maximum and minimum values and the tension in the skyline was calculated.

with $L_1 = 489.700$ $h_1 = 62.70$ $W = 2300$
$L_3 = 226.24$ $h_3 = 3.07$

maximum $Ts = 3063.42$

and with $L_1 = 489.80$ $h_1 = 62.54$ $W = 2280$
$L_3 = 226.06$ $h_3 = 3.25$

minimum $Ts = 3041.73$

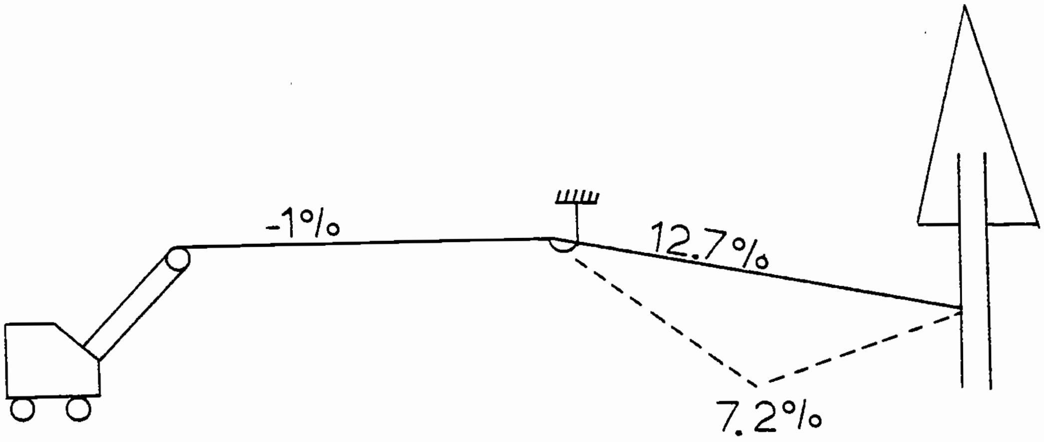
The maximum and minimum predicted values are well within the range of tensions recorded in the field.

The possible errors for the prediction parameters of test 2 and 3 are of the same order of magnitude as test 1 and likewise give values of skyline tension within the range of field measured values. The mainline tension is a function of the same parameters as skyline tension; its sensitivity to measurement errors is analogous to that determined by the skyline sensitivity analysis.

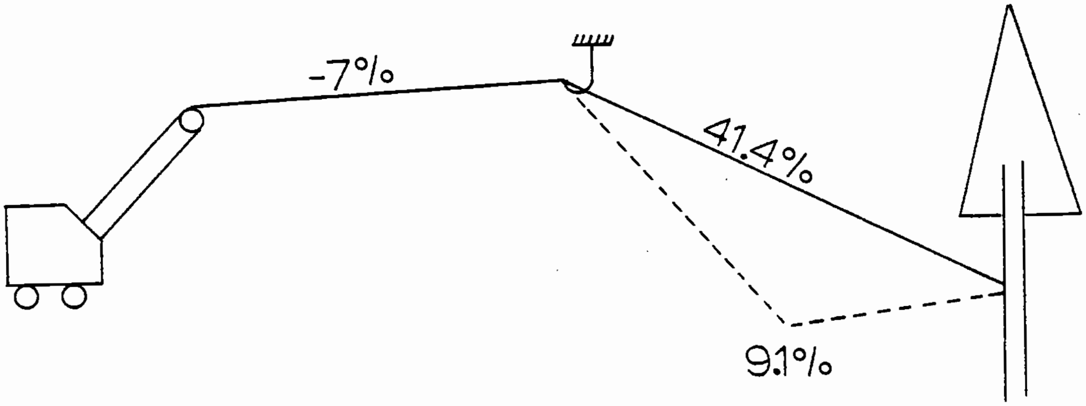
VII. APPLICATION OF RESULTS

Existing Multispan Design Procedures

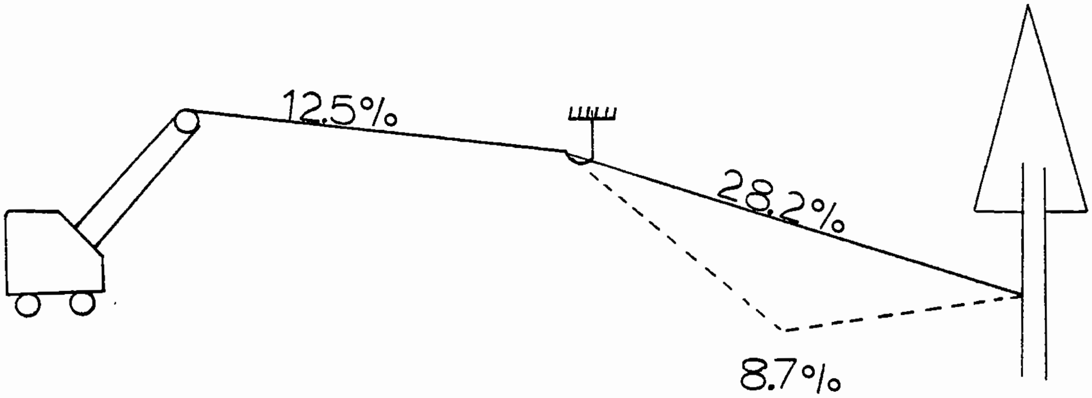
There are limited design data or criteria for determining the maximum allowable midspan deflection or chord slope break at the jack for a multispan system. One recommendation is that 35% is the maximum chord slope break that should be designed (McGonagill, 1977). A second recommendation is that a combination of 35% chord slope break and 6% midspan deflection are design limits (Binkley and Sessions, 1978). Tests 1 and 3 demonstrated that critical conditions are obtainable with chord slope breaks considerably less than 35% (Figure 21). Test 2 demonstrated that it is possible to exceed both the 35% and 6% criteria without encountering a carriage hang-up.



TEST 1



TEST 2



TEST 3

Figure 21

SUMMARY OF CRITICAL TEST RESULTS

Figure 22 is a graph of critical skyline tension to payload ratio for varying chord slopes based upon the catenary analysis. The mainline tension is assumed parallel to the skyline chord between the yarder and support jack. The analysis predicts that for a break in chord slope of 50% (60%-10%), the critical skyline tension to payload ratio is approximately two. If the skyline tension at the jack were 10,000 pounds, a maximum gross payload of 5,000 pounds would be the limit for successful carriage passage. The graph illustrates that as the chord slope break is increased, the gross payload is reduced for a constant skyline tension. It is possible to exceed a 35% chord slope break and successfully pass the intermediate support jack if the gross payload is reduced. Based upon the analysis results, verified by the field test, current recommendations are not always valid.

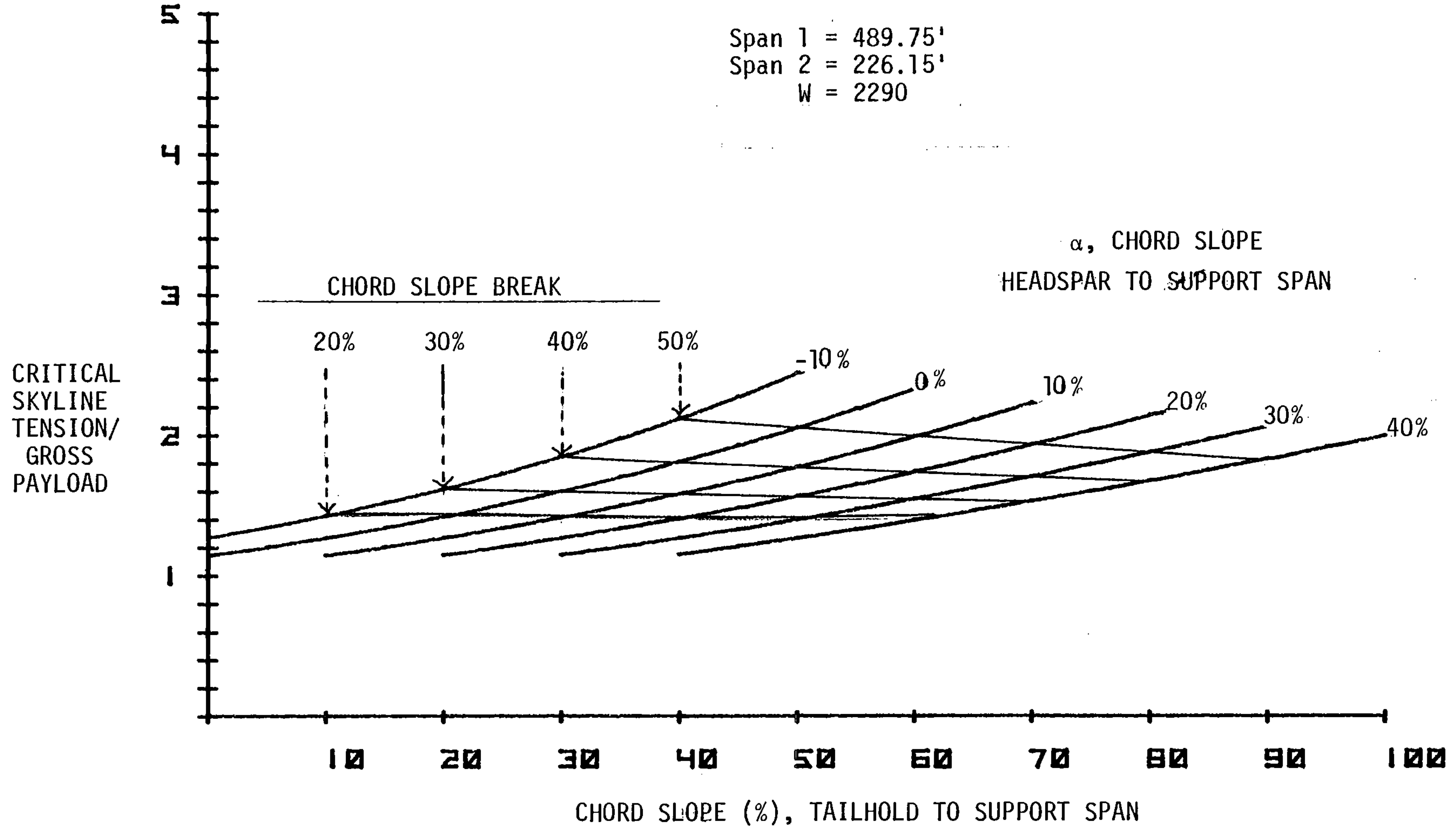


Figure 22

CRITICAL SKYLINE TENSION AS A FUNCTION OF CHORD SLOPE AND MAINLINE ANGLE

Recommended Multispan Design Procedures

A. *Computer Method*

Personal observation and a review of the field test pictures indicated that, at the critical condition, the support jack behaved as though it were frictionless. The skyline was free to slide through the jack until the skyline tension at the jack in adjacent spans was equal. Figure 23 illustrates this condition, where:

T = tension in jack support line

Ts_1 = tension in skyline at the jack, span 1

Ts_2 = tension in skyline at the jack, span 2

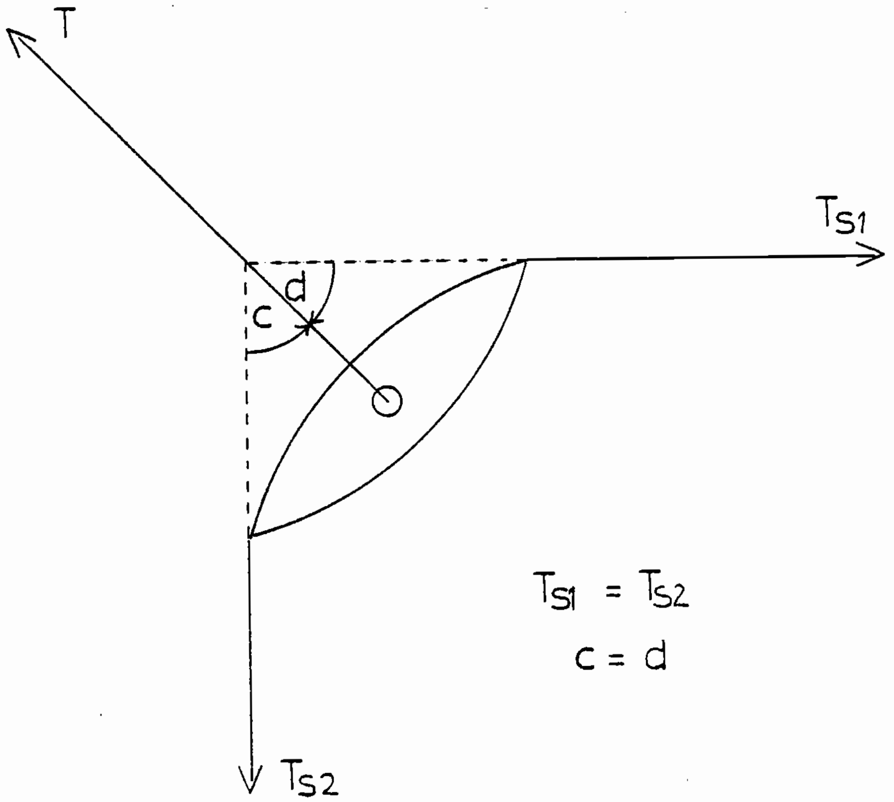


Figure 23

FRICTIONLESS JACK OBSERVATION

MSAP, Carson's (1975) multispan computer program (modified by Sessions to include the effects of the mainline) which assumes a frictionless, rigid jack, would seem to provide an efficient method to determine critical skyline tension. A minor modification was made in the program so that the tension in the skyline would be computed with the carriage as close to the jack as possible (within 0.01% of the payload span).

The following comparison of test data with the modified MSAP program was made to determine the program's adequacy to predict critical conditions for carriage passage. The geometry of each field test was input, and the allowable skyline tension was varied until the net payload equalled the test net payload. In this manner, skyline length corresponding to the critical test conditions was determined. This critical skyline length was input to the load path portion of the program to compute the skyline tension at the head spar which was adjusted to obtain the skyline tension at the jack. This procedure was followed twice - the first time assuming the jack was free to move under load; the second time assuming the jack was rigid. The MSAP payload printouts are contained in Appendix E. Table 7 compares the critical skyline and mainline tension values computed by the Multispan Analysis Program (MSAP) for the cases of jack free and jack rigid with the field measured critical skyline and mainline values.

TABLE 7

FIELD TEST AND COMPUTER ANALYSIS COMPARISON

Test Number	Ts* Field Meas.	Ts* (MSAP) Jack Free	Ts* (MSAP) Jack Rigid	Tm* Field Meas.	Tm* (MSAP) Jack Free	Tm* (MSAP) Jack Rigid
1	3300±750	2954	2944	1900±515	2849	2838
2	4900±750	3532	3517	3200±515	3222	3210
3	2800±750	3165	3155	2100±515	3019	3014

MSAP skyline tension values for test 1 and 3 agree favorably with field measured values, while test 2 values do not. In test 2, the predicted value is lower than the actual value indicating an error on the conservative side. MSAP predicted a greater skyline tension than actual for test 3. Therefore, the error may not always be conservative.

A comparison of skyline tension values predicted for the jack rigid and jack free show a maximum difference of 15 pounds. Based on the measured changes in jack position at critical conditions, the radius of jack rotation for the three tests were 12.28, 6.23, and 24.06 feet, respectively. These radii are not expected to be greatly exceeded in the field. Therefore, the assumption of a rigid jack is valid.

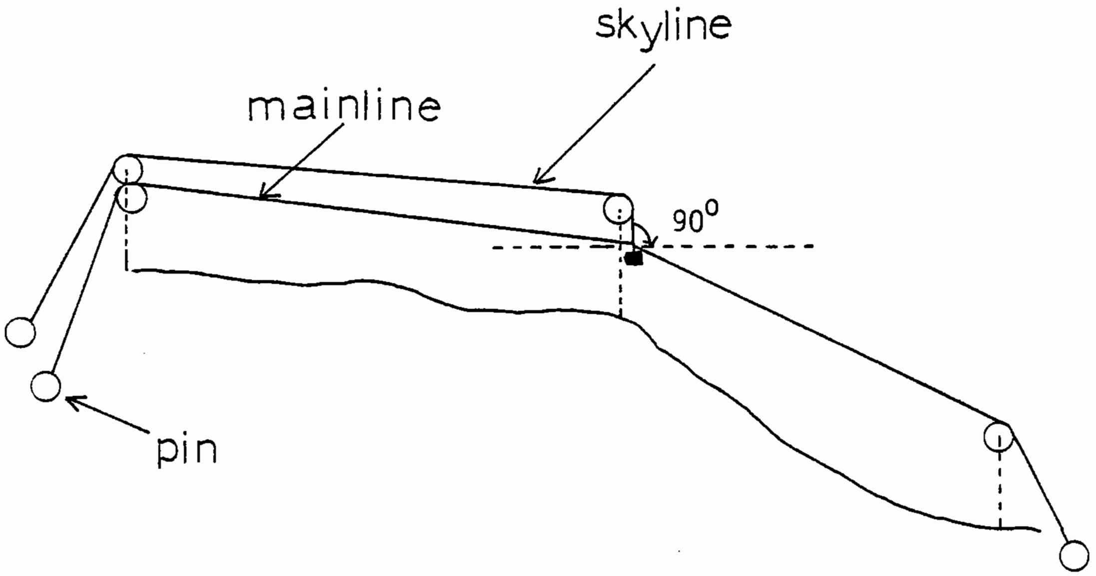
The rigid link analysis modified to include a catenary analysis of the mainline force was incorporated into the MSAP program to predict critical tensions at the jack under various payload and geometry conditions. The program now computes the maximum payload for a specified geometry and skyline tension at designated trial load locations. Using the load and line length of the most critical load location, the skyline tension at the jack is computed and compared with the critical skyline tension as predicted by rigid link. A skyline tension less than the predicted critical skyline tension signifies that the carriage will not successfully pass the support jack.

From Table 7 it can also be observed that the predicted mainline tensions are greater than the actual values, just as in the previously discussed models. Because they are conservative, however, they provide a useful lower design specification unsurpassed by other existing design procedures.

B. Graphical Method

Computer analysis of the load carrying capability of multispan systems is the fastest and, in many cases, the most economical analytical procedure available. In the absence of a computer, the Chain and Board Graphical procedure described by Binkley and Sessions (1978) can be used to determine maximum payloads for various skyline geometries. A slight modification of this procedure to include the effects of the mainline at the jack can also give a good indication of successful carriage passage uphill over an intermediate support jack. The profiles of test 1 and 2 were plotted, then a mainline was attached to the model weight positioned at the support jack. By adjusting the skyline model chain until the skyline segment between the carriage and jack formed an angle of 90° with the horizon ($\theta = 90^{\circ}$), the critical skyline length for successful carriage passage was determined. With the skyline length fixed in this position, the weight was moved back to midspan with the mainline still attached and the critical midspan deflection was measured. Proper mainline angle was maintained by resting the mainline on pins inserted at the points of ground tangency. Figure 24 demonstrates the procedure with the carriage at the jack and midspan, respectively. With careful measurements, a critical midspan deflection was obtained for both tests within five-tenths of one percent of the field measured values. Therefore, it was possible to graphically determine the critical maximum skyline length or midspan deflection for successful carriage passage within the normal range of errors inherent in the chain and board procedure. A conservative prediction of mainline tension required could be obtained using the HP-67 computer program listed in Appendix A to complete the design analysis.

CARRIAGE AT THE JACK



CARRIAGE AT MIDSPAN

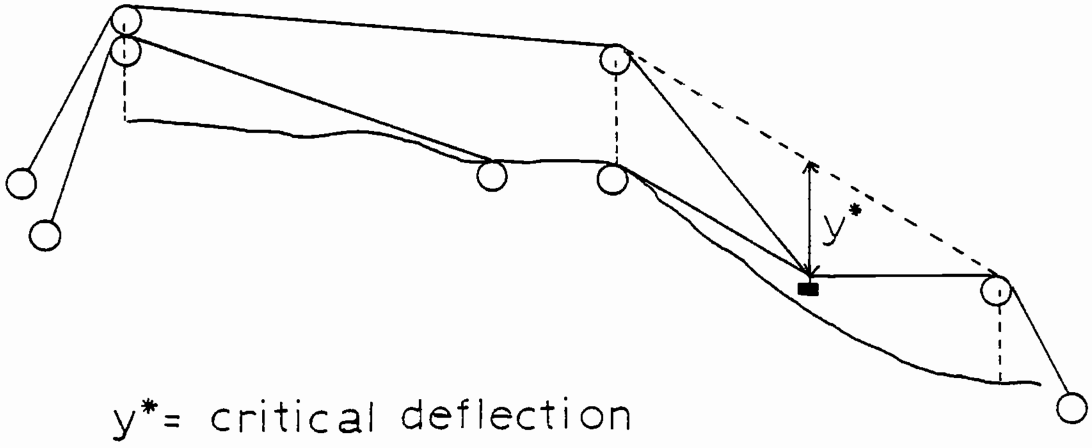


Figure 24

GRAPHICAL DETERMINATION OF CRITICAL MIDSPAN DEFLECTION

C. Field Method

Identifying the condition where the carriage will not successfully pass the jack in the field, although perhaps time consuming, is a relatively easy procedure. In practice, I would expect that this has been done many times in the past where payload and geometry combined to produce near critical conditions. By choking the maximum expected turn to be carried over the intermediate support and yarding it to the jack, the skyline tension can be adjusted until θ is visually observed to be less than 90^{0}. As long as subsequent gross payloads do not exceed the maximum expected turn, one would expect no carriage hang-ups at the jack.

VIII. ECONOMIC IMPLICATIONS

The unpublished existing multispan design criteria are overly conservative in many cases, and therefore, utilization of these guidelines can result in systems operating below their maximum potential. Inefficient use of expensive equipment and crews results in increased operating costs. For example, designing all multispan settings with chord slope breaks no greater than 35% will in some cases require additional intermediate supports and higher fixed costs per setting. A maximum midspan deflection of 6% will result in lower than optimum payloads and higher variable costs. To illustrate the economic significance of applying the design procedures developed in this paper, a typical multispan setting has been analyzed using this method and compared to the existing guidelines. While cost estimates are representative, small variations from actual costs are of little significance due to the comparative nature of the analysis. The following assumptions were used in the comparison.

Yarding Equipment Specifications and Costs

yarder -	RMS Ecologger I 42' tower 1000' - 5/8" skyline 1800' - 9/16" haulback 1800' - 3/8" mainline rigging equipment		
		cost	$110,000
carriage -	Koller Automatic 590 lbs		
		cost	6,000
		TOTAL	$116,000

Setting Geometry and Volume

horizontal span	900 feet
intermediate support location	400 feet
rigged height	50 feet
tailtree rigged height	50 feet
lateral yarding distance	150 feet
volume/acre thinned	20 mbf
setting volume (6.2 ac x 20 mbf/ac)	124 mbf

Figure 25 shows the plotted ground profile for this setting:

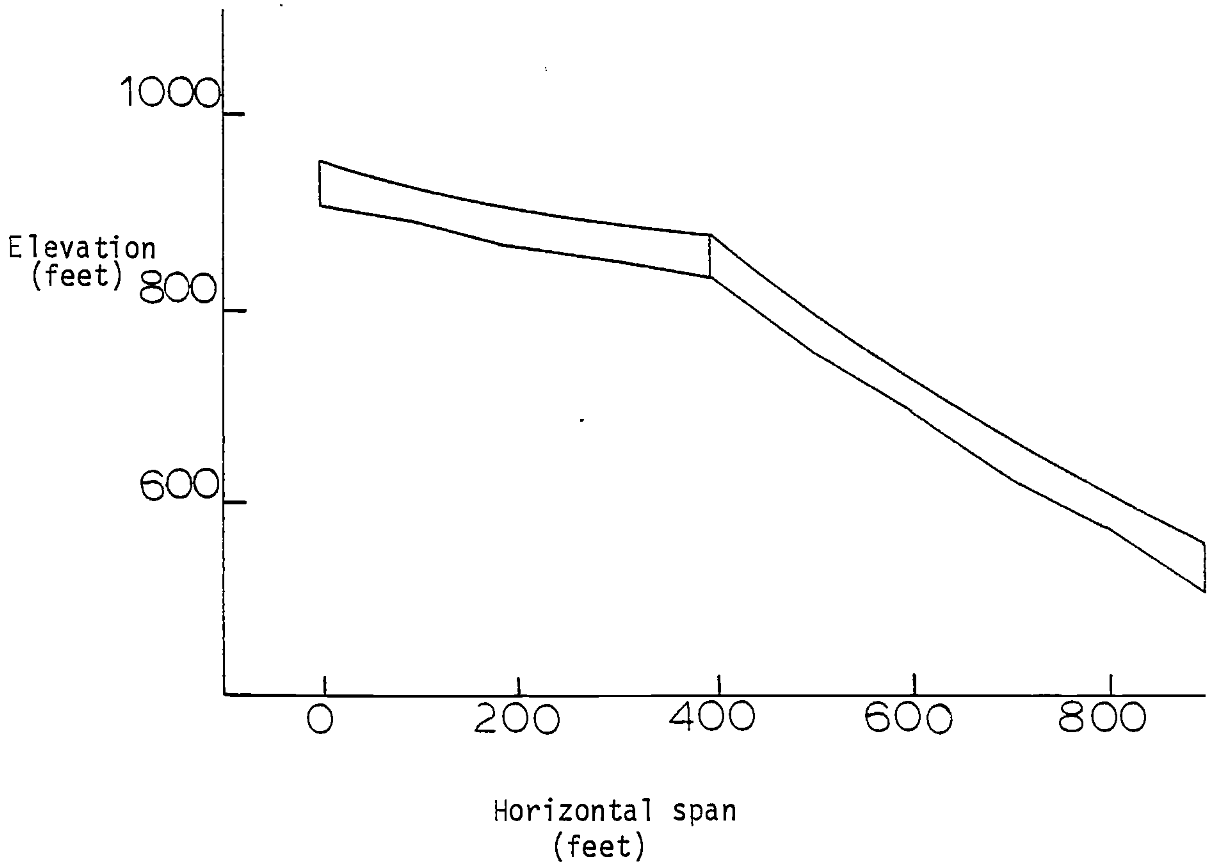


Figure 25

TYPICAL MULTISPAN GROUND PROFILE

Operating Costs

Operating and maintenance[8] .16/1000 ($116,000) = $18.56/hr
Labor, four man crew @ $11/hr = 44.00/hr

Total $62.56/hr

Production Estimates

effective yarding time = 45 min/hour
rig-up time = 2 hour
un-rig time = 1/2 hour
volume/turn
present design[9] = 0.11 mbf
new design[10] = 0.24 mbf

cycle time
present design[11] = 5.14 min/turn
new design[12] = 5.64 min/turn

---

[8] Based on rule of thumb for estimating operatin costs for cable yarders (Sessions, 1978).

[9] Based on a payload analysis using MSAP with 6% deflection (assume one board foot weighs 10 pounds).

[10] Based on a payload analysis using MSAP modified with a new design. The new design predicted a maximum of 10.3% midspan deflection; however, to avoid dragging the carriage, 9% deflection was used. Appendix E contains the MSAP analysis printouts.

[11] Based on Studier (1976). For intermediate skyline, partial cut:

$$\begin{aligned}\text{cycle time} = 2.4589 &+ 0.0029584\ (\text{slope yarding distance})\\ &+ 0.00023413(\text{volume/turn})\\ &+ 0.016285\ \ (\text{lateral yarding distance})\end{aligned}$$

[12] To compensate for the steep chord slope break over the jack, I increased cycle time estimate by .5 min.

Using the following fixed and variable cost/production equations with the stated assumptions, the cost to log the setting based upon the payload predicted by each design procedure can now be calculated.

$$\frac{\text{Fixed Cost}}{\text{setting}} = \frac{(\text{rig-up and down})\text{hr }(\text{operating cost})\$/\text{hr}}{(\text{volume/setting})\text{mbf}}$$

$$\frac{\text{Variable Cost}}{\text{setting}} = \frac{(\text{cycle time})\text{hr/turn}(\text{operating cost})\$/\text{hr}}{(\text{effective hour})\ (\text{volume/turn})\text{mbf}}$$

	Present Design	New Design
Fixed cost =	$\frac{(2.5\text{ hr})(62.56)\$/\text{hr}}{124\text{ mbf}}$	$\frac{(2.5\text{ hr})(62.56)\$/\text{hr}}{124\text{ mbf}}$
	$= \$1.26/\text{mbf}$	$\$1.26/\text{mbf}$
Variable Cost=	$\frac{(5.15/60)\text{hr }(62.56)\$\text{hr}}{(.75)(.11)\text{mbf}}$	$\frac{(5.65/60)\text{hr }(62.56)\$/\text{hr}}{(.75)(.24)\text{mbf}}$
	$= \$65.09/\text{mbf}$	$\$32.73/\text{mbf}$
Total Cost	$= \$66.35/\text{mbf}$	$\$33.99/\text{mbf}$

For this setting then, under the above assumptions the new design criteria would result in approximately a 50% savings in yarding costs.

If you consider the effects of rigging an additional intermediate support tree, as the present design standards would specify for this 46% chord slope break profile, then the fixed costs would increase by about \$1/mbf. However, with an additional intermediate support, the maximum allowable payload for this setting could be increased to at least as much as indicated for the new design. With the same payload capabilities, the new design economic advantage would be considerably reduced to the difference between fixed costs. In settings where the volume/acre being removed is high enough to reduce fixed costs to a fraction of variable costs, such as in this example, additional intermediate supports can be rigged to reduce the advantage of the payload effect. With low volumes/acre, however, extra rigging costs would increase the fixed cost to operating cost ratio, making it economically desirable to rig only one well located intermediate support tree.

Because logging conditions are so variable from setting to setting, it would be difficult to quantify the economic implications of this new design criteria as a general rule. Suffice it to say, that any time you can increase the overall efficiency of a system, some economic advantages are bound to be realized.

IX. CONCLUSIONS

A critical skyline tension and a critical mainline tension were identified as the two conditions necessary for successful carriage passage uphill over an intermediate support jack. Critical skyline tension and critical mainline tension were measured during field tests and compared with predicted values from weightless line, rigid link, and catenary analyses. All three analyses predicted critical skyline tensions within the range of field measured values; however, because of its greater accuracy for all span lengths and lower average deviation from measured values, the catenary model appeared to be the best predictor. The analyses consistently overestimated the critical mainline tension required for successful carriage passage, possibly because critical conditions were never fully attained during the field tests. However, the predicted results still provide useful mainline design criteria when used as a conservative estimate.

An existing computer multispan skyline analysis program (MSAP) was modified using the rigid link analysis to incorporate the predicted critical skyline tension into a useful design procedure. A comparison of MSAP results with measured field values was favorable with skyline tension and conservative with mainline tension, substantiating the validity of the modified MSAP program as a design tool. As an alternative to the computer procedure, a graphical method for determining the critical payload deflection was developed by including the effects of the mainline on cable geometry in the chain and board model. With careful measurements, this procedure predicted the critical payload design deflection within ± 0.5% of the field test data.

The analysis and test results indicated that present multispan design criteria for uphill yarding is overly conservative in many instances. To evaluate the economic effects of designing below system potential, yarding costs/mbf were compared, on a typical setting, based on predicted payloads using present and new design methods. Results of this comparison, based on payload effects only, show a considerable economic advantage exists when using the new design procedure. The same payload could be achieved under the present design guidelines by rigging an additional intermediate support. However, yarding costs would still be lower under the new design procedure due to an increase in fixed costs.

By identifying and developing an analysis capable of predicting the critical boundary conditions for successful carriage passage uphill over an intermediate support, multispan systems can be designed that will operate closer to their full potential. The incorporation of this information into a new design procedure is expected to yield greater economies of operation and increased multispan design confidence not currently available using existing recommendations.

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APPENDIX A

Catenary Solution Program for Critical Skyline and Mainline Tension

HP 67

Step	Key Entry	Step	Key Entry	Step	Key Entry	Step	Key Entry
001	*LBLA	044	ENT↑	087	RCL4	130	2
002	ST00	045	RCL4	088	x	131	-
003	X⇄Y	046	÷	089	RCL1	132	X=0?
004	P⇄S	047	2	090	x	133	GT01
005	ST00	048	÷	091	RCL6	134	P⇄S
006	P⇄S	049	STOE	092	÷	135	GT09
007	RTN	050	e^x	093	RCL2	136	*LBL1
008	*LBLB	051	ENT↑	094	ENT↑	137	RCL8
009	ST01	052	RCLE	095	z	138	ENT↑
010	X⇄Y	053	CHS	096	÷	139	P⇄S
011	P⇄S	054	e^x	097	+	140	RCL8
012	ST01	055	-	098	ST07	141	+
013	P⇄S	056	2	099	RCLD	142	RCL9
014	RTN	057	÷	100	ENT↑	143	+
015	*LBLC	058	RCL4	101	RCL1	144	ENT↑
016	ST02	059	x	102	x	145	PSE
017	X⇄Y	060	2	103	RCL6	146	RCL3
018	P⇄S	061	x	104	ENT↑	147	-
019	ST02	062	x^2	105	RCL0	148	ABS
020	P⇄S	063	RCL1	106	x	149	ENT↑
021	RTN	064	x^2	107	RCL2	150	1
022	*LBLd	065	+	108	RCL7	151	X⇄Y
023	ST03	066	$\sqrt{x}$	109	-	152	X⇄Y?
024	P⇄S	067	ST06	110	x	153	GT02
025	ST0 D	068	RCLE	111	-	154	R↓
026	ST03	069	e^x	112	RCL2	155	R↓
027	P⇄S	070	ENT↑	113	÷	156	ENT↑
028	*LBL3	071	RCLE	114	ST08	157	RCL3
029	0	072	CHS	115	x^2	158	X⇄Y
030	ENT↑	073	e^x	116	ENT↑	159	÷
031	ST05	074	+	117	RCLD	160	RCLD
032	P⇄S	075	RCLE	118	x^2	161	x
033	0	076	e^x	119	+	162	STOD
034	ENT↑	077	ENT↑	120	$\sqrt{x}$	163	GT03
035	ST05	078	RCLE	121	ST09	164	*LBL2
036	P⇄S	079	CHS	122	1	165	RCL9
037	*LBL9	080	e^x	123	ENT↑	166	R/S
038	RCLD	081	-	124	ST+5	167	P⇄S
039	ENT↑	082	÷	125	P⇄S	168	RCL9
040	RCL0	083	RCLE	126	ST+5	169	RTN
041	÷	084	x	127	P⇄S	170	R/S
042	ST04	085	1	128	RCL5		
043	RCL2	086	-	129	ENT↑		

APPENDICES

APPENDIX B

Field Test Equipment Specifications

Martin-Decker UB2 Heavy Duty Tension Indicator
type: Clamp to line
dimensions: 14 1/2" x 11 1/2" x 12"
weight: 33 1.2 lbs.
accuracy: ±3% full scale (25,000 lbs)
manufacturer: Martin-Decker Company
1928 South Grand Avenue
Santa Ana, CA 92705
(714)540-9220

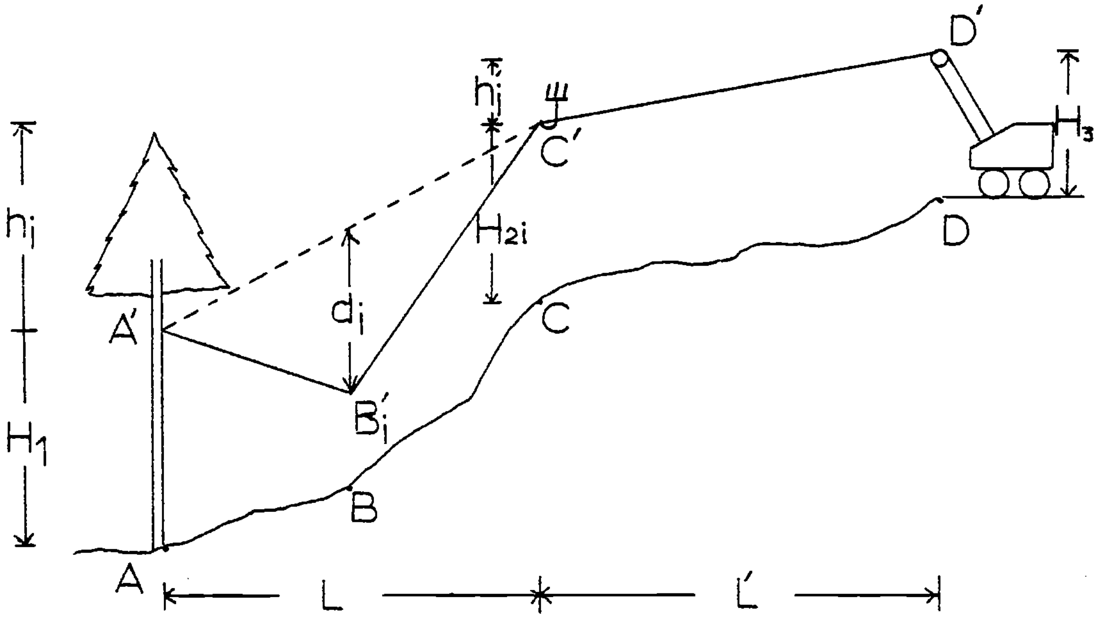
Dillon Remote Indicating Electronic Load Cell System
type: B Meter
weight: 97 lbs.
capacity: 50,000 lbs.
accuracy: Load Cell ±1/4%
manufacturer: W.C. Dillon and Company, Inc.
14620 Keswick Street
Van Nuys, CA 91407
(213)786-812

Rustrak DC Recorder
type: Model 288, 291, 2146, 2194, 300
scale: 50,000 lbs.
accuracy: ±1% full scale
manufacturer: Gulton Industries Inc.
Gulton Industrial Park
East Greenwich, RI 02818
(401)884-6800

Dillon 5000 obs. Capacity Scale
precision: 10 lbs.
manufacturer: W.C. Dillon and Company, Inc.
14620 Keswick Street
Van Nuys, CA 91407

APPENDIX C

Definition of Field Test Variables



a,b,c = terrain points 90° from skyline corridor where theodolite is set

i = number of test run

H_1 = height of tail tree support above ground level

h_i = difference in elevation between tail tree support and jack for run i

H_{2i} = height of support jack above ground level for run i

h'_i = difference in elevation between the support jack and the top of the mainline sheave for run i

H_3 = height of mainline sheave above ground level

A = elevation of terrain point at the base of the tail support tree

A' = elevation of tail tree support block

B = elevation of terrain point at midspan of the left span

B_i = elevation of terrain point at midspan of the left span for run i

B'_i = elevation of skyline for run i

C = elevation of the terrain point vertically below the support jack

C_i = elevation of the terrain point vertically below the support jack for run i

C'_i = elevation of the support jack for run i

D = elevation of the terrain point at the intersection of the vertical from the mainline sheave with the ground

D' = height of the mainline sheave above ground

d_i = left span deflection measured vertically from the left span chord slope to the skyline for run i

L = horizontal length of the left span

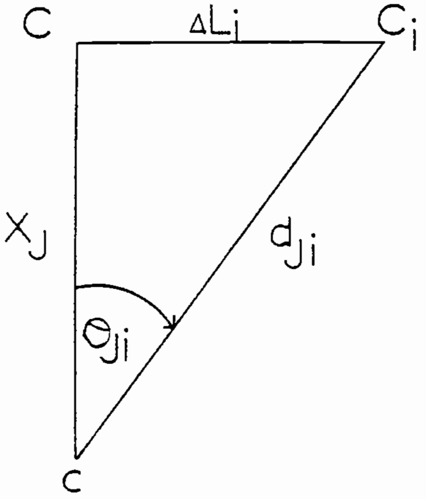
L' = horizontal length of right span

Clearance = vertical distance between B'_i and B_i

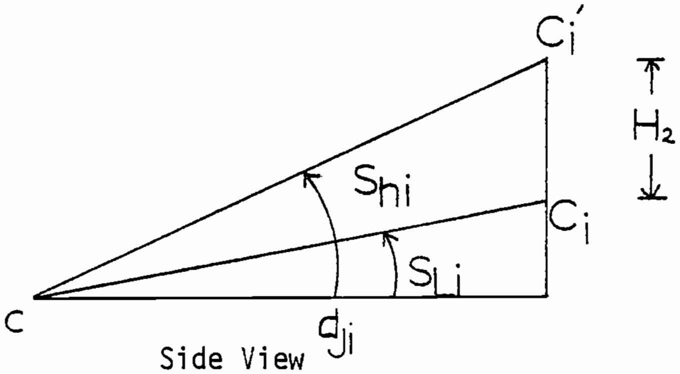
All distance measurements made to the nearest one-tenth foot. All angles recorded to nearest one-half degree or percent.

Description of Field Measured Vertical and Horizontal Angles

At the Jack:



Top View



Side View

ΔL_i = horizontal distance between the initial jack position and its static position for run i

X_J = horizontal distance between the jack station theodolite and the intersection of the initial jack projection with the skyline corridor

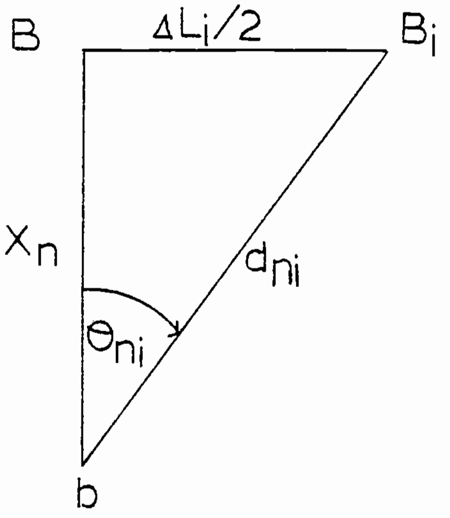
d_{Ji} = computed horizontal distance between the jack station theodolite and the intersection of the static jack projection for run i with the skyline corridor.

θ_{Ji} = horizontal angle measured positive from C to C_i for run i

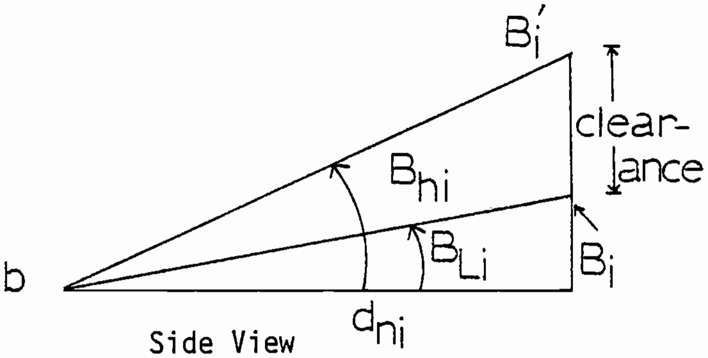
S_{Li} = vertical angle measured positive counterclockwise from the horizon to C for run i

S_{hi} = vertical angle measured positive counterclockwise from the horizon to C'_i for run i

At Midspan:



Top View



Side View

X_n = horizontal distance between the midspan station theodolite and the intersection of the initial midspan projection with the skyline corridor

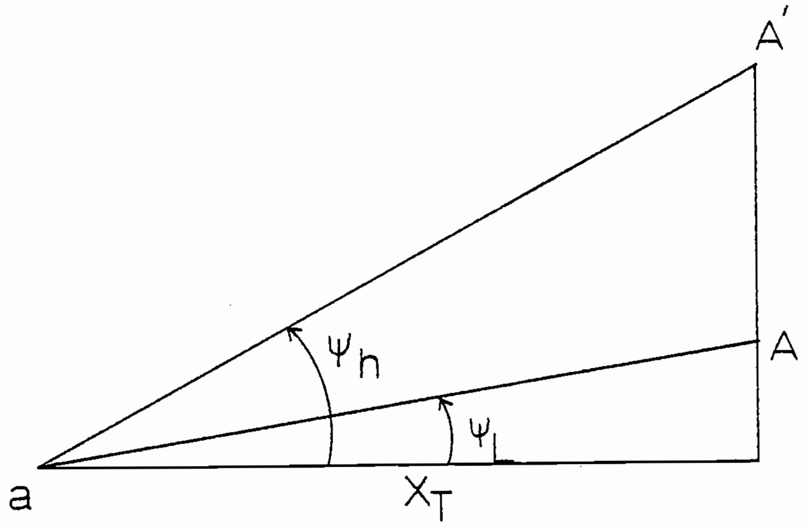
d_{ni} = computed horizontal distance between b and the intersection of the midspan projection for run i with the skyline corridor

θ_{ni} = horizontal angle measured positive from B to B_i for run i

B_{Li} = vertical angle measured positive counterclockwise from the horizon to B_i for run i

B_{hi} = vertical angle measured positive counterclockwise from the horizon to B'_i for run i

At the Tail Tree Support:



Side View

X_T = horizontal distance between tail tree temporary station theodolite and the base of the tail tree, A.

Ψ_L = vertical angle, measured positive, counterclockwise from the horizon to A

Ψ_h = vertical angle, measured positive, counterclockwise from the horizon to A'

Data Reduction Equations

$$\Delta L_i = X_J \operatorname{Tan} \theta_{Ji}$$

$$L_i = \Delta L_i + L$$

$$L'_i = L + L' - L_i$$

$$\theta_{ni} = \operatorname{Tan}^{-1} \left(\frac{\Delta L_i}{2X_n}\right)$$

$$\text{Station } B_i = L' + \frac{L}{2} + \frac{\Delta L_i}{2}$$

$$H_{2i} = \frac{X_J}{\cos \theta_{Ji}} (\operatorname{Tan} S_{hi} - \operatorname{Tan} S_{Li})$$

$$\Delta h_i = H_{2i+1} - H_{2i}$$

$$C_i = C + X_J \operatorname{Tan} \theta_{Ji} \left(\frac{\%\text{ slope from C to C}_i}{100}\right)$$

$$h_i = C_i + H_{2i} - A'$$

$$h'_i = D + H_3 - (C_i + H_{2i})$$

$$\text{Clearance} = \frac{X_n}{\cos \theta_{ni}} (\operatorname{Tan} \beta_{hi} - \operatorname{Tan} \beta_{Li})$$

$$B_i = B + X_n \operatorname{Tan} \theta_{ni} \left(\frac{\%\text{ slope from B to B}_i}{100}\right)$$

$$d_i = \left[H_{2i} + C_i - \frac{h_i}{2}\right] - \left[B_i + \text{Clearance}\right]$$

$$\%d = \frac{d}{L_i}$$

TEST ONE

Initial Fixed Control Data

A	X_T	H_1[13]	B	X_n	C	X_J	D	H_3	W	Haul back	L	L'
906.5	124.2	59.24	936.3	70.5	981.6	85.4	999.2	26	2290	yes	484	231.9

Horizontal Control Data

Run	θ_{Ji}	ΔL_i	L_i	L'_i	θ_{ni}	station B_i
1	0°57'	1.42	485.42	230.48	0°34'	474.61
2	0°31'	0.77	484.77	231.13	0°18'	474.29
3	0°07'	0.17	484.17	231.73	0°04'	473.99
4	0°36'	0.89	484.89	231.01	0°21'	474.35
5	3°20'	4.97	488.97	226.93	2°01'	476.39
6[14]	4°41'	7.00	491.00	224.90	2°50'[15]	477.40
7[16]	3°51'	5.75	489.75	226.15	2°20'	476.77

---

[13] S_L measured to stake 1.7' above A; $S'_L = -7.93°$, $S'_h = 17.95°$

[14] No dynamic carriage passage run attempted - visually estimated that critical conditions were exceeded. Skyline tensioned slightly for run 7.

[15] Field error computation erroneously positioned carriage 0.22 feet left of midspan (based on field error for $\theta_{n6} = 2°20'$)

[16] Critical run.

Vertical Control Data

Run	$\frac{S_{hi}}{S_{Li}}$	H_{2i}[17]	Δhi	C_i[18]	h_i	h'_i	$\frac{\beta_{hi}}{\beta_{Li}}$	Clearance	B_i[19]	d	%d
1	30°11'	45.33		981.6	61.19	-1.73	25°27'	45.39	936.42	14.53	3.0
	3°51'		-.07				-9°32'				
2	30°09'	45.26		981.6	61.12	-1.66	23°10'	42.07	936.36	17.87	3.7
	3°51'		-.07				-9°35'				
3	30°09'	45.26		981.6	61.12	-1.66	21°15'	39.38	936.31	20.61	4.3
	3°51'		0.06				-9°38'				
4	30°13'	45.39		981.6	61.25	-1.79	17°58'	34.72	936.38	25.27	5.2
	3°51'		1.21				-9°33'				
5	30°45'	46.54		981.6	62.40	-2.94	12°49'	27.45	936.73	32.76	6.7
	3°51'		2.08				-9°11				
6	31°08.5'	47.41		981.6	63.27	-3.81	8°38'	22.09	936.91	38.38	7.8
	3°51'		1.43				-9°09'				
7	30°51'	46.76		981.6	62.62	-3.16	10°54'	24.95	936.80	35.30	7.2
	3°51'						-9°09'				

---

[17] All angles turned from stake and flagging 1.4 feet above ground.

[18] % slope from C to C_i = 0

[19] % slope from B to B_i = 17.5

Tension Data

Run	Static Measured			Dynamic Measured	
	Tm	Ts(Jack)	Ts(Midspan)	Tm	Ts(Jack)
1	500	19,200	22,600	500	19,200
2	500	14,500	19,300	400	14,500
3	500	10,900	16,600	500	10,500
4	700	6,700	13,700	700	5,800
5	1600	3,600	10,500	1200	800
6	2300	3,000	8,800	2100	-
7	1900	3,300	9,500	1400	-

TEST TWO

Initial Fixed Control Data

A	X_T	H_1	B	X_n	C	X_J	D	H_3	W	Haul back	L	L'
932.9	-	22.5[20]	971.6	76.04	1006.3	62.0	1000	25.5	2290	yes	216.9	290

Horizontal Control Data

Run	θ_{Ji}	ΔLi	Li	L'_i	θ_{ni}	station Bi
1	0°30'	0.54	217.44	289.46	0°12'	398.72
2	0°30'	0.54	217.44	289.46	0°12'	398.72
3	1°41'	1.82	218.72	288.18	0°41'	399.36
4[21]	4°08'	4.48	221.38	285.52	1°41'	400.69

Vertical Control Data

Run	$\frac{S_{hi}}{S_{Li}}$	$H2_i$	Δh_i	C_i[22]	h_i	h'_i	$\frac{B_{hi}}{B_{Li}}$	Clear-ance	B_i[23]	d	%d
1	21°51'	38.81		1006.35	89.76	-19.66	22°58'	18.52	971.70	10.06	4.6
	-12°42'		0.30				10°13'				
2	22°04'	39.11		1006.35	90.06	-19.96	20°53'	15.31	971.70	13.42	6.2
	-12°42'		0.73				10°13'				
3	22°29'	39.54		1006.48	90.62	-20.52	19°38'	13.17	971.93	15.61	7.1
	-12°36'		1.90				10°24'				
4	23°28'	40.71		1006.75	92.06	-21.96	17°00'	8.91	972.40	20.12	9.1
	-12°27'						10°41'				

---

[20] Hi measured with 50 feet steel tape.

[21] Critical run.

[22] % slope from C to Ci = 10.

[23] % slope from B to Bi = 36.

Tension Data

Run	Static Measured			Dynamic Measured	
	Tm	Ts(Jack)	Ts(Midspan)	Tm	Ts(Jack)
1	1700	15,600	18,900	1400	15,100
2	1400	10,300	15,000	1700	9,400
3	2000	6,500	11,400	2000	4,800
4	3200	4,900	8,600	4000	2,000

TEST THREE

Initial Fixed Control Data

A	X_T	H_1	B	X_n	C	X_J	D	H_3	W	Haul back	L	L'
905.1	-	30.45[24]	939.3	50.7	967.8	45.6	1000	24.4	2290	no	230.3	192.5

Horizontal Control Data

Run	θ_{Ji}	ΔL_i	L_i	L'_i	θ_{ni}	station Bi
1	5°15'	4.19	234.49	188.31	2°22'	309.75
2	2°35.5'	2.06	232.36	190.44	1°10'	308.68
3	2°47.5'	2.22	232.52	190.28	1°15'	308.76
4	3°49'	3.04	233.34	189.46	1°43'	309.17
5	4°04'	3.24	233.54	189.26	1°50'	309.27
6[25]	6°50.5'	5.47	235.77	187.03	3°05'	310.39

[24] H_i measured with 50 foot steel tape.

[25] Critical run.

Vertical Control Data

Run	S_{hi} S_{Li}	$H2_i$[26]	Δh_i	C_i[27]	h_i	h'_i	B_{hi} B_{Li}	Clearance	B_i[28]	d	%d
1	37°53' 4°32'	33.00	 0.02	968.45	65.90	22.95	26°46' 7°54'	18.55	939.84	10.11	4.3
2	37°30.5' 3°47'	33.02	 0.27	968.12	65.59	23.26	23°55' 7°43'	15.62	939.57	13.16	5.7
3	37°32.5' 3°31.5'	33.27	 -.06	968.14	65.86	22.99	22°37' 7°48'	14.18	939.59	14.71	6.3
4	37°45' 4°19'	32.94	 -.03	968.27	65.66	23.19	20°14' 7°51'	12.16	939.70	16.52	7.1
5	37°47.5' 4°21'	32.97	 0.63	968.30	65.72	23.13	19°19' 7°52'	10.77	939.72	17.92	7.7
6	38°24' 4°42'	33.63		968.65	66.73	22.12	17°19' 8°18'	8.42	940.01	20.49	8.7

Tension Data

Run	Static Measured			Dynamic Measured	
	Tm	Ts(Jack)	Ts(midspan)	Tm	Ts(Jack)
1	900	10,900	14,600	900	10,500
2	1100	6,300	11,300	1100	5,100
3	1200	4,700	9,800	1100	3,800
4	1500	3,800	8,400	1400	2,600
5	1700	3,300	7,600	1200	2,200
6	2100	2,800	6,700	3200	2,000

[26] Vertical angle S_{Li} turned from horizon to stakes and flagging 1.0 foot above ground level.

[27] % slope from C to C_i = 15.5

[28] % slope from B to B_i = 26

APPENDIX D

Determination of Combined Uncertainties

Based on the following general relationship from Kline and McClintock (7):

$$U_R = \left[\left(\frac{\partial F\, U_1}{\partial P_1}\right)^2 + \left(\frac{\partial F\, U_2}{\partial P_2}\right)^2 + \ldots\ldots + \left(\frac{\partial F\, U_i}{\partial P_i}\right)^2 \right]^{1/2}$$

where: U_R = combined uncertainty of the result

F = dependent variable

P_i = independent variable

U_i = individual uncertainty of the i^{th} independent variable

The combined uncertainties for the parameters L_1, L_3, h_1, h_3, and W for test one were determined as follows:

$\underline{L_1}$:

$$L_1 = X_J \operatorname{Tan}\theta_J + L$$

$$\frac{\partial L_1}{\partial X_J} = \operatorname{Tan}\theta_J = \operatorname{Tan} 3°51' = 0.067$$

$$\frac{\partial L_1}{\partial \theta_J} = X_J \left(\frac{1}{\cos\theta_J}\right)^2 = 85.4 \left(\frac{1}{\cos 3°51'}\right)^2 = 85.787$$

$$\frac{\partial L_1}{\partial L} = 1$$

U_1 = 0.05 feet

U_2 = 0.00009

U_3 = 0.05 feet

$$U_R = \left[(0.067)^2\ (0.05)^2 + (85.787)^2\ (0.00009)^2 + (1)^2\ (0.05)^2\right]^{1/2}$$

$U_R = \pm 0.05$ feet

<u>L_3:</u>

$L_3 = L + L' - L_1$

$\frac{\partial F}{\partial P_i} = 1$

$U_1 = 0.05$ feet

$U_2 = 0.05$ feet

$U_3 = 0.05$ feet

$$U_R = \left[(0.05)^2 + (0.05)^2 + (0.05)^2\right]^{1/2}$$

$U_R = \pm 0.09$ feet

<u>h_1:</u>

$h_1 = C - A' + H_2$

considering each independent variabel separately;

<u>C:</u>

$U_1 = 0.05$

$U_R = \pm 0.05$

<u>A':</u>

$A' = A + X_T\ (\text{Tan } S'_h - \text{Tan } S'_L)$

$\frac{\partial A'}{\partial A} = 1$

$\frac{\partial A'}{\partial X_T} = \text{Tan } S'_h - \text{Tan } S'_L = \text{Tan } 17.95° - \text{Tan}(-7.93°) = 0.46$

$$\frac{\partial A'}{\partial S'_h} = \frac{X_T}{(\cos S'_h)^2} = \frac{124.2}{(\cos 17.95°)^2} = 137.23$$

$$\frac{\partial A'}{\partial S'_L} = \frac{X_T}{(\cos S'_L)^2} = \frac{124.2}{(\cos (-7.93°))^2} = 126.61$$

$U_1 = 0.05$

$U_2 = 0.05$

$U_3 = 0.000096$

$U_4 = 0.000089$

$$U_R = \Big[(1)^2\ (0.05)^2 + (0.46)^2\ (0.05)^2 + (137.23)^2\ (0.000096)^2 + (.126.61)^2\ (0.000089)^2\Big]^{1/2}$$

$U_R = \pm 0.06$ feet

<u>H_2:</u>

$$H_2 = \frac{X_J}{\cos \theta_J}\ (\text{Tan } S_h - \text{Tan } S_L)$$

$$\frac{\partial H_2}{\partial X_J} = \frac{\text{Tan } S_h - \text{Tan } S_L}{\cos \theta_J} = \frac{\text{Tan } 30°51' - \text{Tan } 3°51'}{\cos 3°51'} = 0.53$$

$$\frac{\partial H_2}{\partial \theta_J} = \frac{X_J \text{Sin } \theta_J}{(\cos \theta_J)^2}\ (\text{Tan } S_h - \text{Tan } S_L) = \frac{85.4 \sin 3°51'}{(\cos 3°51')^2}\ (\text{Tan } 30.51' - \text{Tan} 3°51')$$

$$\frac{\partial H_2}{\partial \theta_J} = 3.05$$

$$\frac{\partial H_2}{\partial S_h} = \frac{X_J}{\cos \theta_J}\ \frac{1}{(\cos S_h)^2} = \frac{85.4}{\cos 3°51'}\ \frac{1}{(\cos 30°51')^2} = 116.13$$

$$\frac{\partial H_2}{\partial S_L} = \frac{-X_J}{\cos \theta_J} \; \frac{1}{(\cos S_h)^2} = \frac{-85.4}{\cos 3°51'} \; \frac{1}{(\cos 3°51')^2} = -85.98$$

$U_1 = 0.05$

$U_2 = 0.00001$

$U_3 = 0.00012$

$U_4 = 0.00009$

$$U_R = [(0.53)^2(0.05)^2+(3.05)^2(0.00001)^2+(116.13)^2(0.00012)^2 + (-85.98)^2(0.00009)^2]^{1/2}$$

$U_R = \pm 0.03$ feet

$U_R = [(0.05)^2 + (0.06)^2 + (0.03)^2]^{1/2}$

$U_R = \pm 0.08$ feet

$\underline{h_3}$:

$h_3 = D + H_3 - C - H_2$

$\frac{\partial h_3}{\partial P_i} = 1$

$U_1 = 0.05$ feet

$U_2 = 0.05$ feet

$U_3 = 0.05$ feet

$U_4 = 0.03$ feet

$U_R = [(0.05)^2 + (0.05)^2 + (0.05)^2 + (0.03)^2]^{1/2}$

$U_R = \pm 0.09$ feet

W:

U_1 = 10 lbs.

U_R = 10 lbs.

100 originals

APPENDIX E

MSAP Analysis

I Critical Skyline Tension As A Function of Deflection

TEST ONE

```
------------------------------------

PROFILE     2       (FILE     2)

T. P. #            X COORD          Y COORD
 1                  0                1000
 2                  5. 9             999. 2
 3                  75. 59           978. 457
 4                  131. 09          983. 174
 5                  205. 875         984. 67
 6                  237. 831         981. 634
 7                  335. 889         962. 023
 8                  434. 307         944. 307
 9                  518. 823         929. 517
 10                 586. 496         921. 058
 11                 686              911. 107
 12                 721. 798         906. 454
```

Jack Moving

```
SKYLINE SIZE   1. 04      LB/FT
MAINLINE SIZE  0. 72      LB/FT
CARRIAGE WT      590

ALLOWABLE WORKING TENSION= 9312    POUNDS

HEADSPAR T. P. =  2               TAILSPAR T. P. =  12
HEADSPAR HT. =   26               TAILSPAR HT. =    59. 24

HORZ. DIST. HEADSPAR TO TAILSPAR= 715. 898
ELEV. DIFF. HEADSPAR TO TAILSPAR= 59. 506

INTER. SPAR 2     T. P. # 5. 82     HEIGHT 46. 76    HORZ.  DIST.  226. 17892
VERT DIFF. -3. 74048

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T. P. # 8. 5   GRD. CLEAR. = 24. 95
    TRIAL LOAD LOCATED AT  471 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF    63
         STRETCHED LENGTH  725. 016   UNSTRETCHED LENGTH  723. 167
             D         H      FORCE ANGLE     FORCE
            226       -4         82. 77       -2882
            471       63         82. 78        2359   NET LOAD=  1700  (  2341)
         AND THE MAINLINE TENSION AT CARRIAGE IS    301
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  723. 167 AND LOAD OF   2341
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1     D 0        H 0        SLOPE  1    PERCENT
             SPAR 2     D 226. 17892    H-3. 74048      SLOPE -13
PERCENT
             SPAR 3     D 715. 898    H 59. 506
    LOAD AT    113, DEFLECTED TO    20. 5    , HEADSPAR TENSION OF    6363
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                    113. 1     20. 5     90. 91             2341 NET LOAD=  1751
                    226. 2     -3. 7     91. 48            -2458
         **HAULBACK REQUIRED**
    LOAD AT    226, DEFLECTED TO    -1. 0    , HEADSPAR TENSION OF    2469
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                    226. 2     -1. 0    136. 25             3386 NET LOAD=  1751
                    226. 2     -3. 7    128. 13            -3864
         **HAULBACK REQUIRED**
    LOAD AT    226, DEFLECTED TO    -0. 1    , HEADSPAR TENSION OF   2951 + 3 = 2954
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                    226. 2     -3. 7     47. 00            -4267
                    226. 2     -0. 1     39. 45             3687 NET LOAD=  1669
         AND THE MAINLINE TENSION AT CARRIAGE IS    2849
    LOAD AT    471, DEFLECTED TO    62. 8    , HEADSPAR TENSION OF    9456
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                    226. 2     -3. 7     82. 84            -2901
                    471. 0     62. 8     82. 78             2359 NET LOAD=  1699
         AND THE MAINLINE TENSION AT CARRIAGE IS    301
    LOAD AT    716, DEFLECTED TO    61. 8    , HEADSPAR TENSION OF    2354
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                    226. 2     -3. 7     85. 00             -722
                    715. 8     61. 8    133. 77             3240 NET LOAD=  1750
         **HAULBACK REQUIRED**
```

Jack Rigid

```
SKYLINE SIZE   1.04     LB/FT
MAINLINE SIZE  0.72     LB/FT
CARRIAGE WT     590

ALLOWABLE WORKING TENSION= 9386    POUNDS

HEADSPAR T.P. =  2             TAILSPAR T.P. =  12
HEADSPAR HT. =   26            TAILSPAR HT. =   59.24

HORZ.DIST.HEADSPAR TO TAILSPAR= 715.898
ELEV.DIFF.HEADSPAR TO TAILSPAR= 59.506

INTER.SPAR 2    T.P.# 6    HEIGHT 45.33   HORZ. DIST. 231.931
VERT DIFF. -1.764

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T.P.# 8.47     GRD.CLEAR. = 24.95
    TRIAL LOAD LOCATED AT  468 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF   63
         STRETCHED LENGTH  724.639   UNSTRETCHED LENGTH  722.777
              D        H     FORCE ANGLE    FORCE
             232       -2         82.56       -2813
             468       63         82.72        2360   NET LOAD=  1700  ( 2341)
         AND THE MAINLINE TENSION AT CARRIAGE IS     303
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  722.777 AND LOAD OF   2341
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1     D 0        H 0        SLOPE  0     PERCENT
             SPAR 2     D 231.931        H-1.764       SLOPE -13    PERCENT
             SPAR 3     D 715.898     H 59.506
    LOAD AT    116,DEFLECTED TO    21.4    ,HEADSPAR TENSION OF    6547
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                     116.0     21.4     90.42            2341 NET LOAD=  1751
                     231.9     -1.8     91.20           -2413
         **HAULBACK REQUIRED**
    LOAD AT    232,DEFLECTED TO     0.8    ,HEADSPAR TENSION OF    2454
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                     231.9      0.8    136.05            3373 NET LOAD=  1751
                     231.9     -1.8    128.20           -3833
         **HAULBACK REQUIRED**
    LOAD AT    232,DEFLECTED TO     1.7    ,HEADSPAR TENSION OF    2942 + 2 = 2944
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                     231.9     -1.8     46.80           -4234
                     232.0      1.7     39.55            3679 NET LOAD=  1689
         AND THE MAINLINE TENSION AT CARRIAGE IS   2838
    LOAD AT    474,DEFLECTED TO    63.1    ,HEADSPAR TENSION OF    9522
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                     231.9     -1.8     82.70           -2803
                     473.9     63.1     82.92            2359 NET LOAD=  1699
         AND THE MAINLINE TENSION AT CARRIAGE IS    295
    LOAD AT    716,DEFLECTED TO    61.7    ,HEADSPAR TENSION OF    2357
        SPAR LOADS      D          H     FORCE ANGLE      FORCE
                     231.9     -1.8     84.89            -695
                     715.8     61.7    133.78            3241 NET LOAD=  1750
         **HAULBACK REQUIRED**
```

TEST TWO

```
PROFILE    3     (FILE    3)

T. P. #          X COORD        Y COORD
 1                0              1000
 2                3              1000
 3                102. 9         1005
 4                202. 8         1008. 5
 5                290            1006. 3
 6                330. 4         997. 4
 7                424. 1         962. 3
 8                506. 9         932. 9
```

Jack Moving

```
          ***CABLE PARAMETERS AND SUPPORT GEOMETRY***

SKYLINE SIZE   1.04     LB/FT
MAINLINE SIZE  0.72     LB/FT
CARRIAGE WT     590

ALLOWABLE WORKING TENSION= 7998    POUNDS

HEADSPAR T.P. =  1              TAILSPAR T.P. =  8
HEADSPAR HT. =   25.5           TAILSPAR HT. =   22.5

HORZ.DIST.HEADSPAR TO TAILSPAR= 506.9
ELEV.DIFF.HEADSPAR TO TAILSPAR= 70.1

INTER.SPAR 2    T.P.# 4.95    HEIGHT 40.71   HORZ. DIST. 285.64
VERT DIFF.-21.62

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T.P.# 6.7  GRD.CLEAR. = 8.91
    TRIAL LOAD LOCATED AT  396 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF   44
         STRETCHED LENGTH  528.734   UNSTRETCHED LENGTH  527.574
              D        H      FORCE ANGLE    FORCE
             286      -22        77.17       -5016
             396       44        68.00        2276   NET LOAD=  1700  (  2111)
         AND THE MAINLINE TENSION AT CARRIAGE IS     872
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  527.574 AND LOAD OF   2111
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1    D 0       H 0        SLOPE  7   PERCENT
             SPAR 2    D 285.64    H-21.62      SLOPE -42   PERCENT
             SPAR 3    D 506.9   H 70.1
    LOAD AT   143,DEFLECTED TO    9.1    ,HEADSPAR TENSION OF   8257
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                     142.8      9.1     94.25           2117 NET LOAD=  1521
                     285.6    -21.6     84.67          -5112
         **HAULBACK REQUIRED**
    LOAD AT   286,DEFLECTED TO  -19.7    ,HEADSPAR TENSION OF   2406
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                     285.6    -19.7    138.29           3174 NET LOAD=  1521
                     285.6    -21.6    121.95          -4082
         **HAULBACK REQUIRED**
    LOAD AT   286,DEFLECTED TO  -18.4    ,HEADSPAR TENSION OF   3509+23 =3532
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                     285.6    -21.6     48.56          -5263
                     285.7    -18.4     33.36           3840 NET LOAD=  1212
         AND THE MAINLINE TENSION AT CARRIAGE IS   3222
    LOAD AT   396,DEFLECTED TO   43.6    ,HEADSPAR TENSION OF   8110
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                     285.6    -21.6     77.23          -5066
                     396.3     43.6     68.00           2277 NET LOAD=  1697
         AND THE MAINLINE TENSION AT CARRIAGE IS   871
    LOAD AT   507,DEFLECTED TO   71.0    ,HEADSPAR TENSION OF   1673
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                     285.6    -21.6     81.37          -1047
                     506.9     71.0    125.03           2576 NET LOAD=  1519
         **HAULBACK REQUIRED**
```

Jack Rigid

```
SKYLINE SIZE   1. 04      LB/FT
MAINLINE SIZE  0. 72      LB/FT
CARRIAGE WT      590

ALLOWABLE WORKING TENSION= 7897. 5  POUNDS

HEADSPAR T. P. =  1               TAILSPAR T. P. =  8
HEADSPAR HT. =   25. 5            TAILSPAR HT. =   22. 5

HORZ. DIST. HEADSPAR TO TAILSPAR= 506. 9
ELEV. DIFF. HEADSPAR TO TAILSPAR= 70. 1

INTER. SPAR 2    T. P. # 5    HEIGHT 38. 81   HORZ.  DIST.  290  VERT DIFF.
-19. 61

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T. P. # 6. 73   GRD. CLEAR. = 8. 91
    TRIAL LOAD LOCATED AT  399 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF   45
         STRETCHED LENGTH  528. 143   UNSTRETCHED LENGTH  526. 998
             D        H      FORCE ANGLE     FORCE
            290      -20        76. 96       -4893
            399       45        68. 10        2272   NET LOAD=  1700  (  2108)
         AND THE MAINLINE TENSION AT CARRIAGE IS     867
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  526.998 AND LOAD OF   2108
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1    D 0       H 0        SLOPE  6    PERCENT
             SPAR 2    D 290     H-19.61       SLOPE -42   PERCENT
             SPAR 3    D 506.9   H 70.1
    LOAD AT   145,DEFLECTED TO   10.3    ,HEADSPAR TENSION OF   8270
        SPAR LOADS     D         H     FORCE ANGLE      FORCE
                    145.0    10.3     93.80             2113 NET LOAD=  1518
                    290.0   -19.6     84.47            -5046
         **HAULBACK REQUIRED**
    LOAD AT   290,DEFLECTED TO  -17.7    ,HEADSPAR TENSION OF   2387
        SPAR LOADS     D         H     FORCE ANGLE      FORCE
                    290.0   -17.7    138.10             3157 NET LOAD=  1518
                    290.0   -19.6    121.98            -4045
         **HAULBACK REQUIRED**
    LOAD AT   290,DEFLECTED TO  -16.3    ,HEADSPAR TENSION OF   3497+20 =3517
        SPAR LOADS     D         H     FORCE ANGLE      FORCE
                    290.0   -19.6     48.35            -5225
                    290.0   -16.3     33.41             3830 NET LOAD=  1234
         AND THE MAINLINE TENSION AT CARRIAGE IS   3210
    LOAD AT   398,DEFLECTED TO   44.4    ,HEADSPAR TENSION OF   8012
        SPAR LOADS     D         H     FORCE ANGLE      FORCE
                    290.0   -19.6     77.00            -4950
                    398.5    44.4     68.06             2273 NET LOAD=  1696
         AND THE MAINLINE TENSION AT CARRIAGE IS    868
    LOAD AT   507,DEFLECTED TO   71.0    ,HEADSPAR TENSION OF   1671
        SPAR LOADS     D         H     FORCE ANGLE      FORCE
                    290.0   -19.6     81.24            -1031
                    506.9    71.0    125.03             2572 NET LOAD=  1517
         **HAULBACK REQUIRED**
```

TEST THREE

```
PROFILE    4     (FILE    4)

T. P. #           X COORD          Y COORD
 1                 0                1000
 2                 100. 03          984
 3                 192. 52          967. 81
 4                 288. 97          944. 18
 5                 385. 49          917. 64
 6                 422. 85          905. 12
```

Jack Moving

```
SKYLINE SIZE   1.04      LB/FT
MAINLINE SIZE  0.72      LB/FT
CARRIAGE WT     590

ALLOWABLE WORKING TENSION= 7607    POUNDS

HEADSPAR T.P. =  1              TAILSPAR T.P. =  6
HEADSPAR HT. =   24.4           TAILSPAR HT. =   30.45

HORZ.DIST.HEADSPAR TO TAILSPAR= 422.85
ELEV.DIFF.HEADSPAR TO TAILSPAR= 88.83

INTER.SPAR 2    T.P.# 2.94    HEIGHT 33.63   HORZ. DIST. 186.9706
VERT DIFF.  21.9886

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T.P.# 4.17     GRD.CLEAR. = 8.42
    TRIAL LOAD LOCATED AT  305 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF   76
         STRETCHED LENGTH  436.678   UNSTRETCHED LENGTH  435.771
                D        H       FORCE ANGLE    FORCE
               187       22         74.46       -2521
               305       76         74.64        2307   NET LOAD=  1700  (  2225)
         AND THE MAINLINE TENSION AT CARRIAGE IS      615
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  435.771 AND LOAD OF   2225
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1    D 0        H 0        SLOPE -12   PERCENT
             SPAR 2    D 186.9706     H 21.9886       SLOPE -29
PERCENT
             SPAR 3    D 422.85  H 88.83
    LOAD AT    93,DEFLECTED TO   28.0   ,HEADSPAR TENSION OF   6642
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                       93.5     28.0    83.50           2239 NET LOAD=  1676
                      187.0     22.0    83.60          -2410
         AND THE MAINLINE TENSION AT CARRIAGE IS    257
    LOAD AT   187,DEFLECTED TO   24.1   ,HEADSPAR TENSION OF   2083
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                      187.0     24.1   132.43           3014 NET LOAD=  1635
                      187.0     22.0   125.13          -3349
         **HAULBACK REQUIRED**
    LOAD AT   187,DEFLECTED TO   25.6   ,HEADSPAR TENSION OF   3188-23=3165
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                      187.0     22.0    42.71          -4264
                      187.0     25.6    36.57           3735 NET LOAD=  1979
    **CARRIAGE WILL NOT PASS JACK MOVING UPHILL**
    **REQUIRED HEADSPAR TENSION FOR PASSAGE=    3224**
         AND THE MAINLINE TENSION AT CARRIAGE IS   3019
    LOAD AT   305,DEFLECTED TO   75.8   ,HEADSPAR TENSION OF   7752
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                      187.0     22.0    74.52          -2550
                      304.9     75.8    74.58           2308 NET LOAD=  1699
         AND THE MAINLINE TENSION AT CARRIAGE IS    617
    LOAD AT   423,DEFLECTED TO   90.7   ,HEADSPAR TENSION OF   1925
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                      187.0     22.0    78.15           -534
                      422.8     90.7   128.43           2839 NET LOAD=  1634
         **HAULBACK REQUIRED**
```

Jack Rigid

```
SKYLINE SIZE   1. 04      LB/FT
MAINLINE SIZE  0. 72      LB/FT
CARRIAGE WT     590

ALLOWABLE WORKING TENSION= 7438    POUNDS

HEADSPAR T. P. =  1               TAILSPAR T. P. =  6
HEADSPAR HT. =    24. 4           TAILSPAR HT. =    30. 45

HORZ. DIST. HEADSPAR TO TAILSPAR= 422. 85
ELEV. DIFF. HEADSPAR TO TAILSPAR= 88. 83

INTER. SPAR 2    T. P. # 3   HEIGHT 33   HORZ. DIST. 192. 52  VERT DIFF.
 23. 59

**TRIAL POINT LOAD ANALYSIS (INPUT 0,0 WHEN DONE)

LOAD ANALYSIS AT T. P. # 4. 19    GRD. CLEAR. = 8. 42
    TRIAL LOAD LOCATED AT  307 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF   77
         STRETCHED LENGTH  436. 670   UNSTRETCHED LENGTH  435. 783
              D        H        FORCE ANGLE    FORCE
             193       24          74. 22      -2465
             307       77          74. 59       2306   NET LOAD=  1700  (  2223)
         AND THE MAINLINE TENSION AT CARRIAGE IS       616
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  435.783 AND LOAD OF   2223
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1    D 0        H 0       SLOPE -13   PERCENT
             SPAR 2    D 192.52     H 23.59      SLOPE -29   PERCENT
             SPAR 3    D 422.85  H 88.83
    LOAD AT    96,DEFLECTED TO    29.3   ,HEADSPAR TENSION OF   6664
        SPAR LOADS     D          H     FORCE ANGLE      FORCE
                       96.3      29.3     83.23            2239 NET LOAD=  1677
                      192.5      23.6     83.48           -2381
         AND THE MAINLINE TENSION AT CARRIAGE IS     268
    LOAD AT   193,DEFLECTED TO    25.8   ,HEADSPAR TENSION OF   2077
        SPAR LOADS     D          H     FORCE ANGLE      FORCE
                      192.5      25.8    132.33            3007 NET LOAD=  1633
                      192.5      23.6    125.17           -3334
         **HAULBACK REQUIRED**
    LOAD AT   193,DEFLECTED TO    27.4   ,HEADSPAR TENSION OF   3180 -25=3155
        SPAR LOADS     D          H     FORCE ANGLE      FORCE
                      192.5      23.6     42.59           -4242
                      192.5      27.4     36.61            3728 NET LOAD=  1989
    **CARRIAGE WILL NOT PASS JACK MOVING UPHILL**
    **REQUIRED HEADSPAR TENSION FOR PASSAGE=     3216**
         AND THE MAINLINE TENSION AT CARRIAGE IS   3014
    LOAD AT   308,DEFLECTED TO    76.5   ,HEADSPAR TENSION OF   7576
        SPAR LOADS     D          H     FORCE ANGLE      FORCE
                      192.5      23.6     74.31           -2483
                      307.7      76.5     74.61            2306 NET LOAD=  1697
         AND THE MAINLINE TENSION AT CARRIAGE IS     615
    LOAD AT   423,DEFLECTED TO    90.7   ,HEADSPAR TENSION OF   1921
        SPAR LOADS     D          H     FORCE ANGLE      FORCE
                      192.5      23.6     78.08            -525
                      422.8      90.7    128.41            2835 NET LOAD=  1632
         **HAULBACK REQUIRED**
```

II Design Payload Analysis Comparison

```
      MULTISPAN ANALYSIS PROGRAM (MAP)
***PROGRAM TO ENTER,PLOT,AND ANALYZE PROFILE***


   PROFILE    5     (FILE    5)

   T.P.#           X COORD         Y COORD
    1                 0             1000
    2               100              980
    3               180              960
    4               300              940
    5               400              920
    6               500              850
    7               600              790
    8               700              720
    9               800              670
    10              900              600
```

```
        ***CABLE PARAMETERS AND SUPPORT GEOMETRY***

SKYLINE SIZE   0.72     LB/FT
MAINLINE SIZE  0.59     LB/FT
CARRIAGE WT     590

ALLOWABLE WORKING TENSION= 12000   POUNDS
```

Clearance = 25 Feet (6% deflection)

```
LOAD ANALYSIS AT T.P.# 7     GRD.CLEAR = 25
    TRIAL LOAD LOCATED AT  600 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF  227
         STRETCHED LENGTH 1001.857   UNSTRETCHED LENGTH  997.132
             D         H      FORCE ANGLE     FORCE
           400        72         66.18        -5904
           600       227         56.62         1671   NET LOAD=  1222  (  1395)
         AND THE MAINLINE TENSION AT CARRIAGE IS   1009
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF  997.132 AND LOAD OF   1395
    PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
             SPAR 1    D 0       H 0       SLOPE -18   PERCENT
             SPAR 2    D 400     H 72      SLOPE -64   PERCENT
             SPAR 3    D 900  H 392
    LOAD AT   200,DEFLECTED TO   51.7   ,HEADSPAR TENSION OF  10318
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                    200.0     51.7     79.86            1417 NET LOAD=   809
                    400.0     72.0     70.49           -5008
          AND THE MAINLINE TENSION AT CARRIAGE IS    250
    LOAD AT   380,DEFLECTED TO   71.9   ,HEADSPAR TENSION OF   8659
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                    380.0     71.9     84.87            1400 NET LOAD=   737
                    400.0     72.0     72.91           -4954
          AND THE MAINLINE TENSION AT CARRIAGE IS    143
    LOAD AT   425,DEFLECTED TO   96.3   ,HEADSPAR TENSION OF   9266
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                    400.0     72.0     63.24           -5528
                    425.0     96.3     51.46            1785 NET LOAD=   930
          AND THE MAINLINE TENSION AT CARRIAGE IS   1119
    LOAD AT   650,DEFLECTED TO  259.7   ,HEADSPAR TENSION OF  11835
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                    400.0     72.0     66.58           -5669
                    650.0    259.7     57.61            1652 NET LOAD=  1209
          AND THE MAINLINE TENSION AT CARRIAGE IS    973
    LOAD AT   875,DEFLECTED TO  381.9   ,HEADSPAR TENSION OF   9247
        SPAR LOADS     D         H     FORCE ANGLE     FORCE
                    400.0     72.0     68.25           -3962
                    875.0    381.9     62.97            1565 NET LOAD=  1052
          AND THE MAINLINE TENSION AT CARRIAGE IS    753
```

Drag Payload = Net Load X 1.5

Drag Payload = 737 X 1.5

= 1105 lbs.

Clearance = 10 Feet (9% deflection)

```
LOAD ANALYSIS AT T.P. # 7    GRD.CLEAR. = 10
    TRIAL LOAD LOCATED AT  600 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF  242
         STRETCHED LENGTH 1004.343   UNSTRETCHED LENGTH  999.607
              D        H      FORCE ANGLE    FORCE
             400       72        64.89       -6425
             600      242        56.45        2663   NET LOAD=  2444  (  2219)
         AND THE MAINLINE TENSION AT CARRIAGE IS   1682
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF   999.607 AND LOAD OF   2219
    PREPARING FOR LOAD PATH BY EXAMINING 1     POINTS PER SPAN
             SPAR 1    D 0       H 0        SLOPE -18   PERCENT
             SPAR 2    D 400     H 72       SLOPE -64   PERCENT
             SPAR 3    D 900   H 392
    LOAD AT    200,DEFLECTED TO   62.2   ,HEADSPAR TENSION OF   9569
        SPAR LOADS    D        H     FORCE ANGLE     FORCE
                   200.0    62.2    79.96            2253 NET LOAD=  1690
                   400.0    72.0    71.96           -5138
         AND THE MAINLINE TENSION AT CARRIAGE IS    398
    LOAD AT    380,DEFLECTED TO   76.4   ,HEADSPAR TENSION OF   5761
        SPAR LOADS    D        H     FORCE ANGLE     FORCE
                   380.0    76.4    91.21            2219 NET LOAD=  1629
                   400.0    72.0    79.07           -4553
         **HAULBACK REQUIRED**
    LOAD AT    425,DEFLECTED TO  105.4   ,HEADSPAR TENSION OF   8430
        SPAR LOADS    D        H     FORCE ANGLE     FORCE
                   400.0    72.0    58.77           -6279
                   425.0   105.4    47.31            3020 NET LOAD=  2009
         AND THE MAINLINE TENSION AT CARRIAGE IS   2083
    LOAD AT    650,DEFLECTED TO  274.2   ,HEADSPAR TENSION OF  11895
        SPAR LOADS    D        H     FORCE ANGLE     FORCE
                   400.0    72.0    65.55           -6109
                   650.0   274.2    57.90            2619 NET LOAD=  2391
         AND THE MAINLINE TENSION AT CARRIAGE IS   1587
    LOAD AT    875,DEFLECTED TO  387.8   ,HEADSPAR TENSION OF   6416
        SPAR LOADS    D        H     FORCE ANGLE     FORCE
                   400.0    72.0    67.97           -2890
                   875.0   387.8    69.13            2373 NET LOAD=  1956
         AND THE MAINLINE TENSION AT CARRIAGE IS    907
```

Drag Payload = Net Load X 1.5

Drag Payload = 1629 X 1.5

= 2444 lbs.

Minimum Design Clearance = 3 Feet (10.4% deflection)

```
LOAD ANALYSIS AT T. P. # 7    GRD. CLEAR. = 3
    TRIAL LOAD LOCATED AT  600 IN SPAN 2 WITH ELEVATION FROM HEADSPAR OF  249
         STRETCHED LENGTH 1005. 858   UNSTRETCHED LENGTH 1001. 115
             D        H      FORCE ANGLE     FORCE
            400       72         64. 32      -6655
            600      249         56. 42       3117   NET LOAD=  3032  (  2596)
         AND THE MAINLINE TENSION AT CARRIAGE IS   2006
```

```
**LOAD PATH ANALYSIS

LOAD PATH BEING COMPUTED FOR LINE LENGTH OF 1001.115 AND LOAD OF   2596
  PREPARING FOR LOAD PATH BY EXAMINING 1    POINTS PER SPAN
       SPAR 1    D 0       H 0      SLOPE -18   PERCENT
       SPAR 2    D 400     H 72     SLOPE -64   PERCENT
       SPAR 3    D 900  H 392
  LOAD AT   200,DEFLECTED TO   67.2   ,HEADSPAR TENSION OF   9335
    SPAR LOADS     D       H    FORCE ANGLE      FORCE
                 200.0    67.2    80.03           2636 NET LOAD=  2098
                 400.0    72.0    72.67          -5243
     AND THE MAINLINE TENSION AT CARRIAGE IS    466
  LOAD AT   400,DEFLECTED TO   73.0   ,HEADSPAR TENSION OF   2375
    SPAR LOADS     D       H    FORCE ANGLE      FORCE
                 400.0    73.0   130.42           3409 NET LOAD=  2005
                 400.0    72.0   115.29          -4116
     **HAULBACK REQUIRED**
  LOAD AT   400,DEFLECTED TO   79.2   ,HEADSPAR TENSION OF   5911
    SPAR LOADS     D       H    FORCE ANGLE      FORCE
                 400.0    72.0    40.80          -7595
                 400.1    79.2    28.30           5479 NET LOAD=  2842
  **CARRIAGE WILL NOT PASS JACK MOVING UPHILL**
  **REQUIRED HEADSPAR TENSION FOR PASSAGE=    5930**
     AND THE MAINLINE TENSION AT CARRIAGE IS   4895
  LOAD AT   650,DEFLECTED TO  280.7   ,HEADSPAR TENSION OF  11924
    SPAR LOADS     D       H    FORCE ANGLE      FORCE
                 400.0    72.0    65.10          -6303
                 650.0   280.7    58.07           3059 NET LOAD=  2946
     AND THE MAINLINE TENSION AT CARRIAGE IS   1871
  LOAD AT   900,DEFLECTED TO  392.4   ,HEADSPAR TENSION OF   2075
    SPAR LOADS     D       H    FORCE ANGLE      FORCE
                 400.0    72.0    68.06          -1103
                 900.0   392.4   118.23           2941 NET LOAD=  2001
     **HAULBACK REQUIRED**
```